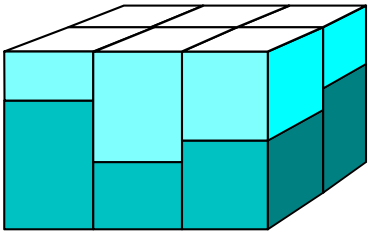
GRABLOX2

Gravity interpretation and modeling software based on 3-D block models

User's guide to version 2.0



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Keywords: geophysics; gravity; 3-D models; modelling; inversion; Occam's method.

1. Introduction

The measured gravity field is caused mainly by the gravitational attraction of Earth's mass, but it's also affected by the centrifugal force due to Earth's rotation and the ellipsoidal shape of the Earth. The international gravity formula (IGF) defines the normal value of the gravity on a reference ellipsoid the surface of which coincides with the mean sea level of the oceans. The gravity field is not uniform, because the masses are not uniformly distributed inside the Earth. Large scale anomalies in the gravity field and the potential defined by the geoid are caused by mass variations deep inside Earth's crust and mantle. Local anomalies that are usually studied in applied geophysics are caused by topography variations and near-surface mass distributions.

The (petrophysical) parameter considered in gravity studies is *density*, ρ, defined as the mass per volume unit [kg/m^3 or g/cm^3]. Density variations are related to variations in the material properties (structure and composition) of the rocks and soil. Therefore, gravity measurements provide an indirect method to study the geological structure of the Earth.

In applied geophysics the measurements give relative changes in the *vertical gravitational acceleration*, g_z [m/s^2 or mgal, where 1 milligal = 10^{-5} m/s^2]. In other words, the difference Δg between different measurement sites is measured using (spring) gravimeters. More accurate absolute measurements that are made for geodetic purposes provide reference points the relative measurements can be tied to. The results are usually represented as Bouguer anomaly, where the data have been reduced to the sea level using IGF and corrected for elevation changes (free-air correction) and the mass between the sea level and measurement point (Bouguer correction). Topographic and isostatic corrections are sometimes made also. Although, the amplitude of gravity anomalies can be hundreds of milligals in large scale studies, they can be less than one milligal in small-scale studies. Therefore, accurate instruments, knowledge on the elevation (and topography), and precise data correction methods are needed in gravity studies.

Gravity field is a vector field ($\mathbf{F} = g_x\mathbf{i} + g_y\mathbf{j} + g_z\mathbf{k}$) which in source free region can be expressed as the gradient of the gravity potential,

$$\mathbf{F} = \nabla\emptyset = \frac{\partial\emptyset}{\partial \mathrm{x}}\mathbf{i} + \frac{\partial\emptyset}{\partial \mathrm{y}}\mathbf{j} + \frac{\partial\emptyset}{\partial \mathrm{z}}\mathbf{k}\,. \tag{1}$$

The gravity gradients that can be measured also are

$$g_{xx} = \frac{\partial^2\emptyset}{\partial x^2}\,,\ g_{xy} = \frac{\partial^2\emptyset}{\partial x\partial y}\,,\ g_{xz} = \frac{\partial^2\emptyset}{\partial x\partial z}\,,\ g_{yy} = \frac{\partial^2\emptyset}{\partial y^2}\,,\ g_{yz} = \frac{\partial^2\emptyset}{\partial y\partial z}\,,\ \text{and}\ g_{zz} = \frac{\partial^2\emptyset}{\partial z^2}\,. \tag{2}$$

The gravity potential of a mass distribution M within volume V can be defined as

$$\emptyset(\mathbf{r}) = G\frac{M}{|\mathbf{r}-\mathbf{r}'|} = G\int_V \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}dV'\,, \tag{3}$$

where $G \approx 6{,}673\cdot10^{-11}$ Nm^2/kg^2 is the universal gravity constant, $\mathbf{r} = (x-x_0)\mathbf{i} + (y-y_0)\mathbf{j} + (z-z_0)\mathbf{k}$ is position vector of the observation point, $\mathbf{r}'$ is position vector of the source point inside the integration volume V, and $\rho(\mathbf{r}')$ is a density distribution the volume integral of which is equal to the mass. The vertical component of the anomalous gravity field that is usually computed is

$$\Delta g(\mathbf{r}) = g_z(\mathbf{r}) = G\frac{\partial}{\partial z}\int_V \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}dV'\,. \tag{4}$$

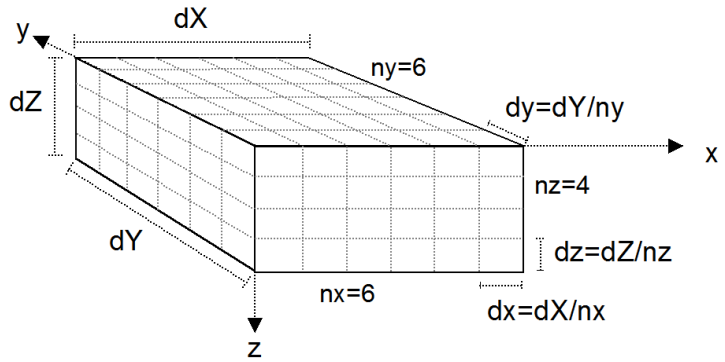
If the density is constant inside the volume it can be taken out from the integral. In that case, the vertical component of the gravity gradient, for example, is

$$g_{zz}(\mathbf{r}) = G\rho\frac{\partial^2}{\partial z^2}\int_V \frac{1}{|\mathbf{r}-\mathbf{r}'|}dV'\,. \tag{5}$$

The unit of gravity gradient is [1/s^2]. However, just like mgal is used for gravity data because of the small amplitude of the geophysical anomalies, Eötvös [1 Eo = 10^{-9} s^{-2} or 0,1 mgal/km] is used for gravity gradient data. For more information about gravity method in applied geophysics, please, see Blakely (1995) or any text book of applied geophysics.

The objective of gravity interpretation is to determine the density contrast and/or the shape and dimensions of the density variations. The general inverse problem does not have a unique solution. Instead, numerical modelling and inversion (parameter optimization) can be only used to construct a possible density distribution that could explain the measurements. Special care must be taken when assessing the geological validity of the geophysical interpretation model since because of the non-uniqueness multiple different models can explain the data equally well. Recently airborne gravity gradient measurements have gained popularity. Since the gravity field and its gradients have different dependency on distance, the gradient data provide valuable constraining information that can improve the inversion result.

Figure 1 illustrates the three dimensional (3-D) block model (a.k.a. voxel model) used in GRABLOX. The rectangular super block representing the volume below the measurement area is divided into smaller brick-like volume elements. Each minor block is assigned constant density value, ρ_{ijk}. The gravity field is then computed as the superposition (sum) of all the minor blocks using equation (4). For more information about 3-D block models, please, see the documentation of the BLOXER program, which can be used to visualize and to edit the 3-D block models.



Block model of size $dX \times dY \times dZ$ (distance units) divided into $N = nx \times ny \times nz$ minor blocks of size $dx \times dy \times dz$ (distance units). The model is aligned with the (geographical) coordinate system.

GRABLOX2 can be used for both forward and inverse modeling (inversion). Gravity field (g_z) and optionally the vertical gravity gradient (g_{zz}) or the six most important components of the gravity tensor (g_{xx}, g_{xy}, g_{xz} g_{yy}, g_{yz}, and g_{zz}) can be modelled. The inversion method optimizes the density of the blocks so that the difference between the measured and the computed gravity (and gradient) data gets minimized. The optimization is based on linearized inversion. The unconstrained inversion uses singular value decomposition (SVD) with

adaptive damping. The constrained inversion utilizes Occam's method where the roughness of the model is minimized together with data misfit. The coefficients of the base anomaly, which is represented by a second degree polynomial, can be optimized separately for the gravity and gradient data. Density of the blocks can be fixed (and weighted) based on a priori information (e.g., petrophysical or drill-hole data). Gradient data can be used together with gravity data in the inversion, but gradient data cannot be inverted alone. After density inversion the distribution of the density variations inside the resulting block model can be used in geological interpretation.

1.1 Notes about this version

GRABLOX2 has quite limited capabilities for model handling and visualization. BLOXER (http://www.cc.oulu.fi/~mpi/softat/) is a separately distributed, free computer program that can be used for more enhanced model editing and visualization. BLOXER can be used, for example, to import a priori density (xyz) and topographic data into the model, export density values along vertical cross-sections of the model, and to interactively edit density, fix/free and hidden/visible status of the blocks. For even more advanced visualization of the 3D density models Voxler by Golden Software is highly recommended.

Unlike previous versions, GRABLOX2 cannot be used to optimize the height of the blocks anymore. To perform two-layer inversion for sediment and soil thickness, please, use GRABLOX version 1.6d (http://www.cc.oulu.fi/~mpi/softat/).

2. Installing the program

GRABLOX2 is a computer program that can be run on a PC with Microsoft Windows XP/Vista/7 operating system and a graphics display with a screen size of at least 1280 × 1024 pixels. In forward modeling the computer memory and CPU requirements are usually not critical factors, because the program uses dynamic memory allocation and the computations are quite simple. However, models with hundreds of thousands of elements may take several hours to compute even on a modern computer. Moreover, inversion of block models with tens of thousands of elements may not be practical because of the increased computation time. The size of continuous memory (1 GB) that must be allocated for the sensitivity matrix restricts the applicability of the 32-bit version. The 64-bit version of GRABLOX2 that can only be run under 64-bit Windows does have this memory restriction.

GRABLOX2 has simple graphical user interface (GUI) that can be used to modify the parameter values, to handle file input and output, and to visualize the gravity data and the model. The user interface and graphics are based on the DISLIN graphics library.

The program requires following files: GRABLOX2.EXE and DISDLL.DLL (the 32-bit executable file and DISLIN dynamic link library) or GRABLOX64.EXE (the 64-bit version does not require the DLL file). The distribution file (GRABLOX2.ZIP) also contains a short description file (_README.TXT), a user's manual (GRABLOX2_MANU.PDF), some example data (*.DAT & *.GAT) and model files (*.INP & *.BLX). To install the program simply uncompress (with 7zip or Winzip) the distribution files into a new folder. To be able to start the 32-bit executable file from a shortcut that locates in a different directory, the DISDLL.DLL file should be copied or moved into the system folder. Alternatively, one can modify the PATH environment variable. When running the program over local network one should provide the network drive with a logical drive letter (e.g., Explorer/Tools/ Map network drive…).

3. Getting started

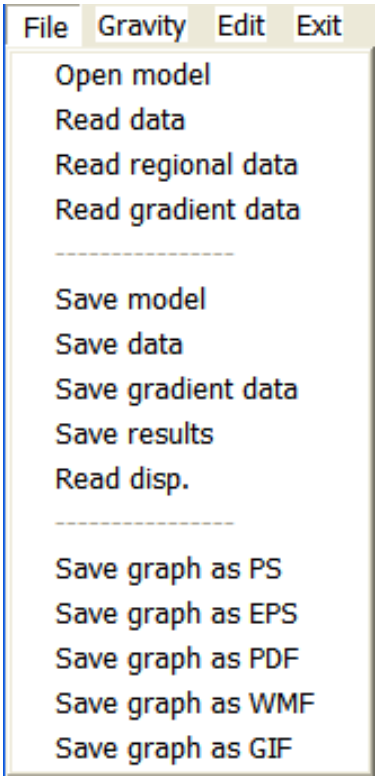
After startup the program shows a standard file selection dialog, which is used to provide the name of the input model file (*.INP). If the user cancels the file selection operation the GRABLOX2.INP file will be used. If this file does not exist default parameters are used and the file will be created automatically. The parameters of individual blocks are read from a separate *.BLX file. Before the user interface is built up, the program reads graph parameters from the GRABLOX2.DIS file. If this file does not exist default parameters are used and the file is created automatically. The program runs in two windows: 1) the console (shell) window and 2) the graphical user interface (GUI) window. The console window provides runtime information about the current status of the program. The information appearing on the console window is also stored in a log file (GRABLOX2.LOG).

After the initial model and the system parameters have been defined the user interface is build up (see the Appendices) and a density map of the top layer is shown (cf. Appendix A1). The model can be visualized using *Layers* and *Sections* push buttons. Repetitive use of *Layers* and *Sections* push buttons will show successive layers or sections. *Crossing dir* button swaps between (West-East directed) X-sections and (South-North directed) Y-sections. The <-/-> button is used to reverse the direction of layer and section swapping.

Compute button is used to perform forward computation. *Map data* button plots the data as a 2-D colored contour or image map along with a 3-D view of the model and a short description on some parameters (see Appendix B1). If the computation of gravity gradients is activate, *Gravity/Gradient* button swaps the map between the two data types and *Grad. component* button swaps the map between the six tensor components. *Profiles* (and *Crossing dir*) button will display a single X- or Y-directed (interpolated) profile across the data area. Model and system parameters are changed using the text fields on the left control panel. *Update* button must be used to validate the changes. The computational settings can be changed using the items in the *Gravity* menu. Most of the controls on the right control panel are inactive before measured data have not been read in. To learn more about data interpretation, please, refer to chapters 5 and 6.

4. The user interface

4.1 File menu

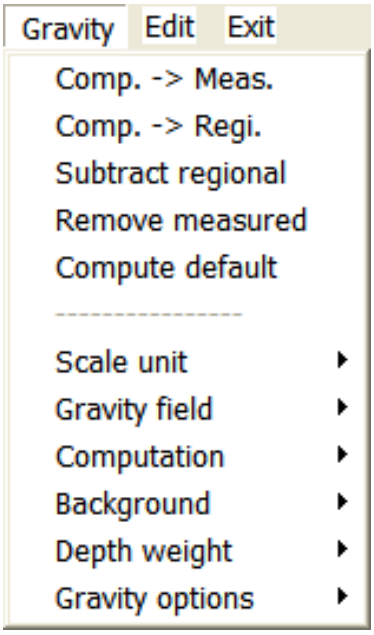


Open an existing model file (*.INP)
Read in data for interpretation and comparison (*.DAT)
Read in regional data (stationary gravity field) (*.DAT)
Read in gravity gradient data (*.GAT)
Save the model into a file
Save the data (computed & measured) into a file
Save the gradient data (computed & measured) into a file
Save the results (description & data) into a file
Read in new graph parameters from a *.DIS file
Save the graph in Adobe's Postscript format
Save the graph in Adobe's Encapsulated PS format
Save the graph in Adobe's (Acrobat) PDF format
Save the graph in Windows metafile format
Save the graph in GIF (graphics interchange format).

These menu items will bring up a standard file selection dialog that can be used to provide the file name for open/save operation. The model parameters are saved in two files: the first one (*.INP) defines files general properties and the second one (*.BLX) defines the actual block model data. When saving the results, GRABLOX2 stores text information into a *.OUT file. By default, gravity data are in a *.DAT file whereas gravity gradient data are in a *.GAT file. All data files are stored in (ASCII/ISO8859) text format. Binary block (*.BLX) files can be used to handle very large models more efficiently. See chapter 7 and the BLOXER manual for more information about the block file format.

GRABLOX2 does not support direct printing. Instead, graphs first need to be saved on a disk and then a suitable third party program (e.g., Adobe Acrobat Reader, Ghostview, Paint Shop Pro, Xnview, etc.) can be used to open and print the files. The graphs are saved in landscape A4 size as they appear on the screen. The GIF file is the only bitmap format (size 2970×2100 pixels). The Enhanced Postscript file does not include preview bitmap.

4.2 Gravity menu



Computed data is made as (synthetic) measured data
Computed data is made as (constant) regional field
Regional field is subtracted from measured data
Remove all information about measured data
Create a default model based on measured data
Define dimensions in meters, kilometers, feet or miles
Swap between total field and anomalous field
Define computation mode: g_z, $g_z + g_{zz}$ or g_z + 6 gradients
Define background density mode
Define depth weighting mode
Set and define other computational options.

- *Comp→Meas* and *Remove measured* are useful when testing the program and using it for educational purposes.
- *Comp→Regi* can be used to define a regional field using the current model. Alternatively, one can use the *Read regional data* menu item.
- *Subtract regional* will remove the current regional field (if defined) and/or base anomaly from the measured data. Removal of the regional trend reveals finer features in the mapped data. The resulting dataset can be saved to disk for future use with the *File*/*Save data* item.
- *Compute default* is used to create an initial model. It is useful after new measured data has been read in, because will give the super-block some reasonable coordinates based on the data. If the data are regularly gridded the model is also discretized automatically, i.e., the model is divided into minor-blocks that are positioned below the data points (z coordinates also). When dealing with irregularly sampled data the user should perform the discretization manually. Note that 2-D surface data and profile data are handled differently and profiles that are not aligned with coordinate axes are not supported.
- When GRABLOX2 reads in data it does not know the units of the coordinates and distances. The *Scale unit* item defines the actual volume of the block model, and hence, the correct amplitude of gravity effect. Therefore, after reading in the data the user should

supply correct scale (meters, kilometers, or miles) before continuing with the modeling or interpretation.

- The computed gravity field (g_c) is the sum of 1) the gravity effect of the model (g_m), 2) the user defined base anomaly (g_b) and 3) external regional field (g_r)

$$g_c = g_m + g_b + g_r \,. \tag{6}$$

If regional field (g_r) has been defined the *Gravity field* item can be used to include and exclude the regional field to give either the total field or the anomalous field. The base anomaly (g_b) is always added to the computed response.

- *Computation* defines the three modes of the gravity computation:
  1. The traditional gravity effect, i.e., the vertical component of the gravity field (*Gz*)
  2. The gravity effect and the vertical gravity gradient (g_z & g_{zz})
  3. The gravity effect and the full gravity tensor, i.e., the six gradient components.

Note that this menu item cannot be used after measured data (gravity and gradient) has been read in – the data itself defines the components that are going to be computed.

- *Background* defines the three modes of background density:

  1. Normally, the background density has a constant value defined by the *Bg dens* field on the left control panel. In this case, the background density is subtracted from the density values of each minor block. Thus, if the density of the block is equal to the background value it has no effect in the computed gravity anomaly.
  2. In large-scale crustal studies the background density value can be defined as a function of depth using the mean density of each layer. In this case, the mean density is subtracted from the density of each minor block. This method is useful in large-scale studies and when the density is assumed to increase downwards.
  3. The background density can also be defined as the mean density of all the model blocks. This method allows a simple way to define floating background value. If the density increases downwards this method is not as good as the second one.

The purpose of the background density is to remove (or reduce) the effect of the four sides of the super block especially when the model deals with absolute density values. If the contrast between the mean density of the model and the background is large, the effects of the internal density variations of the model will not be visible at all.

If the background density is zero, the inversion will resolve residual density where the mean density of the modelled volume should be added to give geologically realistic density values. When absolute density values, for example, from petrophysical samples are used to define the initial model, the background value cannot be zero anymore. In that case, the background value should be set to the mean of the sample values or, as usual, to the density value used in Bouguer and topographic corrections (e.g., 2670 kg/m^3).

Depth weight defines three modes of depth weighting used in density inversion. Normally, the near-surface blocks have much larger sensitivity than the deep blocks. Consequently, the inversion will generate a model where the masses are concentrated close to the surface, which is likely to be geologically unrealistic. Depth weighting will place the mass distributions at their "correct" depth by enhancing the importance and sensitivity of the blocks as a function of depth. The depth weighting is discussed more in chapter 5.3.

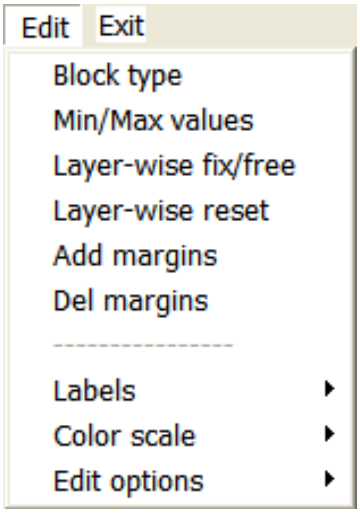
The *Gravity options* sub menu contains following items:

- *Autosave* enables/disables saving the model and data between each inverse iteration. Since the inversion of large models is usually made overnight, this allows to see how the model evolves in the inversion and to start the inversion again from any previous model.
- *Discontinuity* enables/disables the use of discontinuity information in the Occam inversion. The discontinuity information is stored in the model file as a second parameter with the help of the BLOXER program. If the model file does not contain discontinuity parameter, this menu item will be inactive. See chapter 5.5 for more information.
- *Inversion* enables/disables inversion and defines whether or not the sensitivity matrix (Jacobian) will be computed automatically during forward computation when data have been read in. For example, when *Comp→Meas* item is used to set computed (synthetic) data to measured data, inversion (and related menus and controls) is not enabled until it is manually enabled with this menu item. Note that when actual measured data is read in, the

inversion is enabled by default. However, if the model is very large the program may be unable to allocate memory for the Jacobian. In this case GRABLOX2 disables the inversion and computes only the forward solution. After a new model with smaller amount of elements has been defined this menu item can be used to enable the inversion again.

- *Gradient weights* item provides a quick way to set the global weights for each gravity gradient (tensor) component. Alternatively, one needs to edit the *G-scale* parameter for each gradient component manually.
- *Rotate gradient data* is used to rotate the measured gravity gradient data horizontally, i.e., to perform tensor rotation around vertical z-axis. If the measurement lines are not aligned with the geographical coordinate axes, it is advantageous to rotate the data coordinates so that the model will be aligned with the data. However, airborne gravity gradient data (e.g., AirFTG®) is normally aligned with geographical coordinate axes and, therefore, tensor rotation must be performed to adjust the tensor data accordingly. Note that tensor rotation is different from coordinate rotation and that vertical gradient data (g_{zz}) are not affected by the horizontal rotation. Also note that currently GRABLOX2 does not support rotation of data coordinates – that must be made using some third-party (spreadsheet) program.

4.3 Edit menu



Use either equal-height or increasing height blocks
Define min & max parameter value (and color scale)
Set fix/free/hidden status of the blocks per layer
Set the density of the blocks per layer
Add margin areas around the super block
Remove the outermost margin area
Define parameter labels shown in the graphs
Change the color scale
Set and define other settings

- Although the *xyz* dimensions of the blocks can vary, all blocks have equal size by default. In the alternative block type (*Block type 2*) the height of the blocks will systematically increase downwards by the value of the topmost layer of blocks. For example, layer thickness increases as 100, 200, 300, 400, 500 m giving depths 0, 100, 300, 600, 1000,

1500 m. The alternative block sizing thus reduces the resolution at the bottom but helps decreasing the total number of blocks. Note that block type cannot be changed if the *Shift* only editing mode is active (the second item in left control panel).

- *Min/Max values* item changes the limiting density values on the color scale (below the layers or sections view) and determines the absolute minimum and maximum density values used in the inversion. These values also determine the maximum parameter steps in SVD based inversion.

> *Note about the input dialogs*: The parameter values are passed to the program via a text string using a simple input dialog that appears on the display. The dialog does not contain normal Cancel button. Therefore, to cancel the input operation one should close the dialog with force (press the cross icon at the top-right corner) or provide an empty input line. This rule applies to all other similar input dialogs.

- *Layerwise fix/free* option allows setting the fix/free status (weights) and the visible/hidden status of the blocks of each layer manually. Weights have integer values that range between -101 and 100. Zero weight will fix the density of the block during inversion. Weight equal to 1 and 100 make the density fully free and values ranging between 2 and 99 provide decreasing weight so that 2 is almost fully fixed and 99 is almost fully free. Negative weight value will set the block hidden (the block will still carry the value of the weight). Note that computationally, hidden block has density that is equal to the background density. Hidden blocks are not drawn in layer and section views. See chapter 5.2 for more information about the fix/free status.
- *Layerwise reset* option allows setting the density value of the blocks for each layer manually. Fixed and hidden blocks are not affected.
- *Labels* either removes the layer and section labels totally, or shows the numeric value of the density, block height, block depth, fix/free status (weights), or the discontinuity (if available).
- *Add margins* & *Del margins* can be used to add a single row/column of blocks horizontally around the whole block model at once. Margins are important when interpreting gravity gradient data, because they can be used to move the edge effects (due to the density contrast between the block and the background) outside from the computation area. When

adding margins an input dialog appears and the user is asked to provide the width of the margin blocks.

- *Color scale* item is used to choose between normal rainbow scale, inverted rainbow scale, normal grayscale, inverted grayscale and a special (seismic/temperature) red-white scale.

The *Edit options* submenu contains following items:

- *Show/Hide grid* can be used to clarify the contour/image maps as well as the layer and section graphs.
- *Contour/Image* item swaps the display mode of gravity data between a contour map and an image map where data are plotted as colored rectangles. Contour plots are smoother but more time consuming if there are lots of data points. Highly irregularly spaced data should be as an image map because the interpolation can create artifacts.
- *Show/Hide regional* item enables/disables plotting the regional field or base anomaly. When the regional field is not shown one can swap between computed and measured data map to see the visual difference between them more easily.
- *Show/Hide difference* enables/disables plotting the difference between computed and measured data as a map. When the difference is not shown one can swap between computed and measured data map to better see the visual difference between them.
- *Swap map area* changes the limits of the data and layer maps so that they are either based on the model area or the data area. If wide margins have been added to the model, this option allows the user to focus either on the model area or the data area.
- *Difference abs/%* item defines the difference between the computed and measured data either as absolute difference (data units) or as relative error (in percents). The relative error is computed with respect to the (max-min) variation of the measured data.

4.4 Exit menu

Widescreen item is used to restart the GUI so that it fits the (old) 4:3 displays or (modern) widescreen and laptop displays better. When entering widescreen mode the user needs to provide a value for width/height ratio that is normally between 0,7 and 0,8. However, when working with two separate displays having extended display area even smaller values should be needed.

Exit item is used to confirm the exit operation. On exit the user is given an opportunity to save the current model and the results, provided that exit is made without an error condition. On exit, the program first asks the name for the model files (*.INP & *.BLX) and then the name of the results file (*.OUT). If the user cancels the save operation after choosing to save the model or results, the default filename GRABLOX2.* will be used.

Errors that are encountered before the GUI starts up are reported in the GRABLOX2.ERR file. When operating in GUI mode, run-time errors arising from illegal parameter values are displayed on the screen. Some errors, however, cannot be traced and given an explanation. The most typical problem is perhaps a corrupted GRABLOX2.DIS file that prevents the program to start up properly. This problem can be circumvented simply by deleting the *.DIS file. A missing or incorrectly named *.BLX file can also cause troubles. Please, note that most messages that appear on the console window are stored also into a run-time log file GRABLOX2.LOG. This file is written over when the program is restarted.

4.5 Left control panel

Update button is used (and must be used) to validate the changes made to the parameter text fields. Once the *Update* button is pressed, the parameters defining the position, size, and discretization of the block model are read in, checked for erroneous values and the old values are replaced with the new ones.

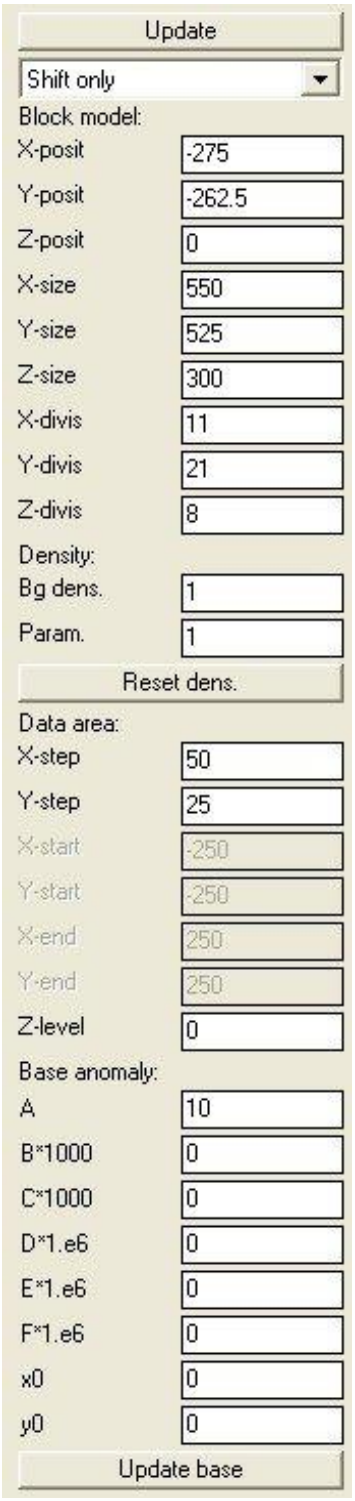
Note that the use of *Update* button invalidates any existing computed results and a new forward (or inverse) computation needs to be made.

The list widget below the *Update* button defines how the block parameters will be affected when the *Update* button is pressed.

1. *Shift only* mode updates only the *xyz* position of the whole block model. The size and the discretization of the super block cannot be changed in *Shift only* mode. This is the default mode and it is purpose is to protect the model from accidental changes.
2. *Ignore* mode allows easy redefining of the size and discretization of the super block. As the name implies, the existing relationship between the position and the density of the

blocks is ignored totally. The density of an arbitrary block $p(i,j,k)$ remains the same but it will most likely move to a totally different position inside the model if the discretization (indexing) changes.

3. *Preserve* mode uses simple 3-D nearest neighbor interpolation to define new density values of the blocks when the model is resized, rediscretized, or repositioned. For example, if the position of the super block is shifted, the anomalous target remains more or less at the same geographic position, but its relative position (indexing) inside the super block will change. Note that 3-D interpolation of densely discretized and large models can be very time-consuming.



The following text fields define the position, size and discretization of the super block:

1. *X* position (easting) of the SW corner of the super block
2. *Y* position (northing) of the SW corner of the block
3. *Z* position (depth to the top) of the super block
4. *X* size of the super block (in EW direction)
5. *Y* size of the super block (in NS direction)
6. *Z* size or height of the super block (downwards)
7. *X* discretization (number of blocks) in EW-direction
8. *Y* discretization (number of blocks) in NS-direction
9. *Z* discretization (number of blocks) in vertical direction.

In GRABLOX2 the true dimensions (distances) of the block model (and computation grid) are defined using the *Gravity*/*Scale unit* menu item. The given rectangular coordinates do not need to be actual geographic map coordinates. To be able to better model geological strike directions, for example, the data and the model should be defined using rotated coordinates.

The next two text fields define two density parameters:

1. *Bg dens* defines the user defined background density value, ρ_0 (g/cm^3)
2. *Param* defines the default density value used to reset the model into, ρ_1 (g/cm^3).

Note about density units: In GRABLOX2 the density is defined in units [g/cm^3]. Use the BLOXER program to modify density values if required. For example, divide by 1000 (actually, multiply with 0,001) if densities are given as kg/m^3.

Reset dens button resets the density of the whole model to the value defined in *Param* text field. Note that fixed and hidden blocks are protected and will not be affected.

The gravity field [mgal] and gravity gradients [Eo] are always computed using some density contrast $\Delta\rho = \rho_i - \rho_0$ [g/cm^3], that is to say, the difference between the density of the blocks (ρ_i) and the background density (ρ_0). The method used to define the background density is chosen using the *Gravity*/*Background* menu item. When *Given value* mode is active, the value of background density provided in *Bg dens* field will be subtracted from the density values of each minor block. Note that density values can be absolute (background density and density range is based on petrophysical data, for example, ρ_0= 2,7 g/cm^3 and 2,0 < ρ < 3,6 g/cm^3) or relative (background value is zero or arbitrary, e.g. -0,6 < ρ < +1,2 g/cm^3). The computed gravity results will be exactly the same if the density contrasts with respect to the value of background value are the same.

In forward computations the rectangular computation grid is defined by the seven text fields below *Reset dens* button:

1. *X-step*: spatial step between computation points in *x* direction, *dx*
2. *Y-step*: spatial step between computation points in *y* direction, *dy*
3. *X-start*: *x* coordinate (easting) of the grid start position, *x1*
4. *Y-start*: *y* coordinate (northing) of the grid start position, *y1*
5. *X-end*: *x* coordinate (easting) of the grid end position, *x2*
6. *Y-end:* *y* coordinate (northing) of the grid end position, *y2*
7. *Z-level*: constant *z* level (height or elevation) of the computation grid, *zh*.

If the width of the computation grid is zero (e.g., *x1 = x2 or y1= y2*) the computations are made along a single profile that extends from (*x1, y1*) to (*x2, y2*) and *X-step* is used as a distance step between the computation points along the profile. In this case the profile is aligned either with x axis (*y1= y2*) or y axis (*x1 = x2*). Alternatively, a more general (azimuthal) profile from (*x1, y1*) to (*x2, y2*) can be defined, if *Y-step* is set equal to zero (*dy* = 0). In this case the *X-step* is used as a step between the points along the profile. Naturally, profile data can be plotted only as a profile plot (no contour or image maps). However, in this case the data are drawn exactly without any interpolations. Also note that depending on the current status of data extent (defined by *Edit/Edit options/Swap map area* menu item) the layer view shows only the part of the model below the profile.

Note about Z-level and X- and Y-steps: In forward modeling the limit values of the data are the same for gravity data and gravity gradient data. The elevation and the sample spacing, however, are defined separately for gravity and gradient data. Their value depend on the status of the active data that defined by the *Gravity/Gradient* button in the right control panel. In other words, when gravity data is active (is currently mapped or plotted) *Z-level* defines the elevation of the gravity data and when gradient data is active it defines the altitude of gradient data. This allows simultaneous modeling ground gravity and airborne gravity gradient data. Different *X-* and *Y-step*s allow computing (and plotting) gravity and gradient data with different sample spacing.

Measured data are assumed to be irregularly spaced. The computations are always made at the actual data locations (*x,y,z*). Therefore, grid start and end positions are inactive after measured data have been read in. Moreover, when data has been read in *X-step* and *Y-step* define grid spacing used in contour and image maps. When the data are irregularly spaced, x and y steps should be edited manually to reduce possible contouring artifacts.

Note about data elevation: The z coordinates (elevation or topography) of the measured data are used only if they are provided with the data AND the *Z-level* is equal to the top of the super block (*Z-level = Z-posit.*). Otherwise, the response will be computed at the constant elevation defined by the *Z-level*. This method allows inspecting the effect of height in gravity computations. To compute the gravity field on the surface of the block model, t must set the *Z-level* very close to the *Z-posit* value (but do not make them equal).

The remaining eight text fields (*A, B, C, D, E, F, x0, y0*) are used to define a computational base anomaly as a second degree polynomial of a form:

$$g_b(x,y) = A + B(x-x_0) + C(y-y_0) + D(x-x_0)^2 + E(y-y_0)^2 + F(x-x_0)\times(y-y_0)\ , \qquad (7)$$

where x_0 and y_0 define the shifted origin for the base function. By default the origin (x_0, y_0) is located at the middle of the super block. Because the amplitude changes of gravity anomalies are small compared to the distances, the values of *C* and *D* are scaled (multiplied) by 1000 and the values of *E* and *F* are scaled by 10^6. Thus, if dimensions are defined in meters, the linear and second order coefficients are defined as mgal/km and mgal/km^2, respectively. The base anomaly is always added to the computed gravity anomaly even if external regional field has been read in.

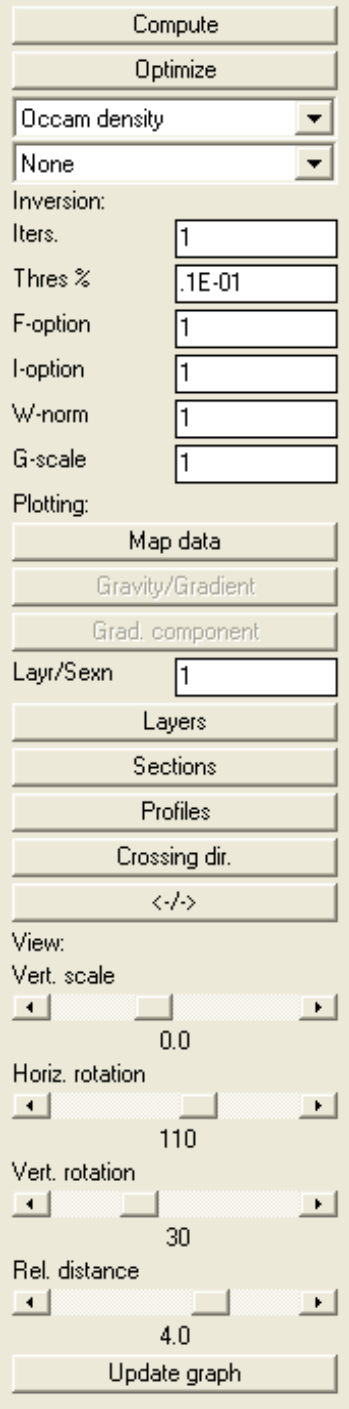
<u>*Note about the base anomaly:*</u> The base anomaly is defined separately for the gravity data (g_z) and each gravity gradient component (g_{xx}, g_{xy}, g_{xz}, g_{yy}, g_{yz}, and g_{zz}) depending on the current status of the data defined by the *Gravity/Gradient* button. In other words, when gravity data is active (is currently mapped or plotted) the coefficients are related to the base anomaly of the gravity data and when gradient data is active the coefficients are related to that data component.

Update base button at the bottom of the left control panel is used to update the changes made to the base level immediately without the need to do full forward computation.

4.6 Right control panel

The *Compute* button is used to perform the forward computation using the current values of the model and system parameters. The *Optimize* push button is used to start the inversion. Note that depending on the total number of minor blocks and the amount of computation points, the inversion can take a considerable amount of time.

The list widget below the *Optimize* button defines the three inversion modes:



1. *Base* optimizes the coefficients of the base anomaly,
2. *Density* optimizes the density of the free minor blocks using SVD based method
3. *Occam density* optimizes the density of the free minor blocks using Occam's method, where both the data misfit (difference between the measured data and the computed response) and the model roughness are minimized.

The second list widget defines which coefficients or a combination of coefficients of the base anomaly is going to be optimized when *Base* optimization is performed. Note that in *Occam d*ensity inversion the linear coefficients (*A, B,* or *C* or *A, B* and *C*) of the base anomaly of the gravity data (not the gradient data) can be optimized together with density values. One must remember to select *None* if one does not want the base anomaly to be optimized together with density. Note that in practice combined inversion of base anomaly and block parameters requires that some density values are fixed based on additional *a priori* information.

The optimization of the base anomaly is performed either on the gravity data or gravity gradient data depending on the current status of the mapped data defined by the *Gravity/Gradient* button.

The following five text fields define some inversion related options. See chapter 6 for more information about the abovementioned inversion options.

1. *Iters* defines the number of iterations made during one inversion run.
2. *Thres %* defines the strength of damping in SVD based inversion. Normally, the threshold should be at the level of the smallest singular values that are still informative.

The smaller the threshold value is the weaker is the damping. Note that the value shown as the threshold is actually multiplied by 100. Thus, the default value 0.01 (%) is actually 0.0001.

3. *F-option* provides numerical (real) value of an additional parameter to the inversion. Its role depends on the selected inversion mode. In SVD based inversion it determines the maximum step controlling the convergence. In Occam inversion it is used as a Lagrange multiplier controlling data fit vs. model smoothness.
4. *I-option* provides numerical (integer) value of an additional parameter to the inversion. Its role depends on the inversion mode – in Occam inversion it is used to control the rigidity of fixed blocks whereas in base inversion it is used to shift the fit towards the bottom or the top of the gravity or gradient anomaly.
5. *W-norm* increases or decreases the depth weighting as a function of depth. The value should be changed from the default value 1,0 only if the inversion results seem to overestimate or underestimate the density values at the deep parts of the model. For example, *W-norm* value 2,0 enforces twice as strong depth weight at the bottom of the model and a value 0,5 gives only half as strong depth weighting.
6. *G-scale* defines global data weight for individual data components when gravity data and gradient data are optimized together. Depending on the current status of the mapped data (*Gravity/Gradient* button) the weight is related to gravity data or one of the gravity gradient components. The value should be changed from the default value only if the inversion seems to emphasize or de-emphasize one of the data components too much. For example, decreasing the global weight of *Gxy* gradient component to 0,1 will make the corresponding data error 10 times smaller and, consequently, gives that data component less importance in the inversion.

The next three push buttons are used to show and define the current gravity data.

- *Map data* button shows the gravity data as a colored 2-D map. If measured data has been defined, repetitive use of the *Map data* button will swap the view between the computed and measured data, the data error (difference between measured and computed data) and the regional or base response data. The map type can be changed between contour or image map using *Contour/Image* item in the *Edit/Options* submenu. Plotting of data error and regional field can be omitted using *Show/Hide difference* and *Show/Hide regional* items in the *Edit/Options* submenu.

- *Gravity/Gradient* button swaps the current data component between gravity field and gravity gradient. The item is active only if gradient computation has been enabled (using *Gravity/Computation* menu item).
- *Grad comp.* button swaps the current data between different gradient components when full gravity tensor data is being computed. The item is active only if gradient computation has been enabled (using *Gravity/Computation* menu item).

Layr/Sexn text field shows the index number of the current layer or section when the model is being visualized (see the meaning of the buttons below). It is possible to jump from one layer or section to another by first giving a new value for the index number manually and then pressing the *Layers* or *Sections* button.

- *Layers* button is used to show the density values across a horizontal layer.
- *Sections* button is used to show the density values across a vertical cross-section.
- *Profiles* button is used to show the computed and measured data and the regional/base anomaly as XY graphs over the data area. The data is either gravity or gravity gradient depending on the status of current map defined by the *Gravity/Gradient* button.
- *Crossing dir* button is used to change the direction of the sections views and data profiles between (vertical) SN and (horizontal) WE directions.
- <-/-> button is used to change the rotation direction of contours/image maps, layers, sections and profiles when the corresponding buttons are pressed.

When the *Layers*, *Sections*, and *Profiles* buttons are pressed multiple times the current layer, section or profile is rotated, that is to say it changes to the next or previous one depending on the direction defined <-/-> button. After the last (or first) layer, section or profile the view jumps back to the first (or last) one. One can jump directly into a desired layer or section by first providing the index number on the *Layer/Sexn* text field and then pressing the corresponding push button.

If the data covers a two-dimensional area it assumed to be irregularly sampled and the profile graphs show the data interpolated along (imaginary) *x* or *y* directed profiles, the interval of which are based on values of the *X-step* and *Y-step* text fields in the left control panel. This means that the profile response displays the original data only if the data are regularly gridded

and the steps are equal to that of the data. If the data are highly irregular, the DISLIN contouring algorithm used in GRABLOX2 may not work well and the profile response shows up incorrectly. Some improvement can be made by changing the data representation from a contour map to an image map using the *Contour/Image* item in *Edit/Options* submenu. Alternatively, the data could be mapped on a regular grid beforehand using some third party interpolation software (e.g. Golden Software Surfer or Geosoft Oasis Montaj).

GRABLOX2 suits also 2.5-D interpretation of single profile data. In this case, the data should be aligned with either the x or y axis so that the *Gravity/Compute default* can be used to generate a proper initial model automatically. Consequently, if the profile is aligned with y axis, the model will be discretized along the *x* and *z* directions, the *y* discretization (*Y-divis*.) is set equal to one, and the strike length (*Y-size*) is made so large that the model appears to be two-dimensional. Although it is possible to compute the forward response along general profiles that are not in x or y direction, a 2.5D model cannot be constructed properly, since the model is always discretized along x and y axes. Note that 2.5-D inversion methodology has not been tested thoroughly. It is likely that the depth weighting needs to be redefined for models having elongated strike length.

Normally, the vertical depth axis is plotted in 1:1 scale with horizontal axes in X and Y-section views. *Vert. scale* slide control can be used to stretch or squeeze the depth axis. It is useful if the height of the model is considerably smaller than its horizontal dimensions. The other three slide controls (*Horiz. rotation, Vert. rotation and Rel. distance*) are used to change the view point of the small 3-D model view next the main graph. The *Update graph* button must to be used to validate the changes made to the slide controls and to redraw the current graph.

5. Inversion and related information

The three inversion modes are:

1. *Base* SVD based optimization of the base response (level and gradients)
2. *Density* SVD based (unconstrained) optimization of the density
3. *Occam* (constrained) Occam inversion of the density

Density values are limited by the minimum (*Min*) and maximum (*Max*) values of the color scale below the *Layer* and *Section* graphs. The limit values are set using the *Min/Max values* item in the *Edit* menu.

5.1 Regional field

The measured gravity field is always affected by mass distributions both near to and far away from the study area. The purpose of the regional field in GRABLOX2 is to account for (and subtract) the gravity effect of all those masses that are located around and below the volume of the 3D super-block. Although the regional field can be defined almost arbitrarily, the important thing is not to remove any gravity effects that might be explained by density variations inside the volume of the 3D block model.

The three ways to define the regional field in GRABLOX2 are:

1. User-defined base anomaly (defined by a second degree polynomial),
2. Regional field is read in together with the measured data (*Read data*), or
3. Regional field is read in from a separate file (*Read regional*).

The choice of regional field is one of the most important factors of successful gravity interpretation. Best results are obtained if the regional field is interpreted separately using a larger regional model and gravity data that extends (horizontally and vertically) 2–5 times farther than the actual interpretation model of the study area. The block size of the regional model can be 2–10 times larger than what will be used in local modelling. The important thing is to set the discretization of the local and regional models so that the block boundaries (sides and bottom) of the local model fit the discretization of the regional model. Once the

regional-scale inversion has been made and an acceptable model has been found, the volume of the local study area is removed (hidden) from the regional model (with BLOXER) and the regional, large-scale gravity anomalies of the surroundings are computed at the data locations of the local study area and saved into file. Alternatively, surface fitting or low-pass filtering (e.g., Surfer, Geosoft, Fourpot) can be used to define the regional trend of the gravity anomaly. These methods, however, are somewhat vague, because they do not take into account the real physics and the depth extent of the targets.

The regional trend of the gravity data can be defined using the optimization of the parameters of the base anomaly. Although a second degree polynomial used in GRABLOX2 cannot describe as complicated regional effects as external files, it is often a good approximation to the regional gravity effects. Also note that the base anomaly is useful also if the data and/or regional field for some reason are not in level with the measured gravity data.

Note about the base anomaly: Base anomaly is always added to the computed response. Nonetheless, it can be used together with the user defined regional field also. Therefore, optimization of the coefficients of the base anomaly provides a method to adjust the first and second degree behavior of the regional field. Furthermore, in *Occam* inversion the base level and/or linear trend ($A+Bx+Cy$) of the base anomaly of the gravity field can be optimized together with the density values (although this can be ambiguous).

The *Gravity/Subtract regional* item can be used to remove the regional field from the measured data and the new data can be saved into a file (*File/Save data*). Theoretically, there should not be any difference if the inversion is made using total field or anomalous field. However, if the regional trend has been removed from the original data, the visual inspection of the data and fit between measured and computed data is often much easier. Moreover, the absolute minimum and maximum values and the dynamic range of the data will be different. As a consequence, inversion uses different data weighting and is likely to yield slightly different results. The users are advised to work with anomalous field if a very strong regional trend is included into the original gravity data.

5.2 Fix/free status

The fix/free status defines whether the block is included into the inversion (optimization) or not. In GRABLOX2 it serves also as weight factor defining relative importance of the fixed density values. The weight factor is utilized only in Occam inversion. The fix/free value is zero (0) for a totally fixed block (not optimized at all), and either one (1) or one hundred (100) for a totally free block. Fix/free values ranging from 2 to 99 define variable weights. Note that in a *.BLX file, the fix/free status is stored as an integer value.

The *Layerwise fix/free* item can be used to manually set a constant fix/free value for each layer. Note that it can also be used to set the hidden/visible status of the blocks per each layer. Hidden blocks are removed totally from the computation. As such they represent the density of the background medium. For more advanced editing of the fix/free and hidden/visible status one should use the BLOXER program.

5.3 Depth weighting

Normally unconstrained (and un-weighted) gravity inversion tends to put the excess mass mainly in (or remove the missing mass mainly from) the uppermost blocks, because their sensitivity is much greater than that of the deeper blocks. Consequently, the resulting inverse model is not likely to be geologically realistic. The concept of depth weighting (Li and Oldenburg, 1996 and 1998) tries to overcome this problem. Basically the idea is to multiply the elements of the sensitivity matrix and the difference vector with depth dependent function of form

$$w_d = (z+z_0)^a , \tag{8}$$

where z is the depth of a block from the top of the super block, z_0 is a scaling value that depends on the size of the blocks, and a is an exponent that depends on the geometric form of the potential field. The gravity field has $1/r^2$ dependency on the distance from the source. However, experimental value $a = 1$ gives better convergence in 3-D gravity inversion.

The problem with depth weighting is that it does not take *a priori* data into account and possible near surface mass distributions will get incorrectly positioned. To circumvent these

problems GRABLOX2 has an option to automatically relax the depth weighting based on the value of the current RMS error. When the RMS error decreases during the inversion so does the depth weighting until it disappears when RMS reaches level of 0,2 %. In practice, however, full depth weighting should be used and the other two options (relaxed or discarded) should be used just to test the effect of depth weighting.

The status of the current depth weighting method can be derived from the last line of the information text next to the model and response graphs. After the inversion mode (*Base optimization, SVD inversion, Occam inversion*) the first integer number defines the depth weighting mode (0= none, 1= relaxed, 2= full). The second number shows whether or not the automatic model saving is active or not (0= no, 1= yes). If the model file includes discontinuity information the third number would indicate if it is active or not (0= no, 1= yes).

5.4 Normal SVD based inversion

Base and *Density* inversion modes are based on a linearized inversion scheme similar to that defined in Jupp and Vozoff (1975) and Hohmann and Raiche (1988). The optimization uses singular value decomposition (SVD) and adaptive damping method defined in Pirttijärvi (2003). For the sake of clarity, the basics of the linearized inversion method are discussed in the following.

The objective of the numerical inversion is to minimize the difference or misfit (**e** = **d**-**y**) between the measured data, **d** = (d_1,d_2,…,d_M**)** and the computed response **y** = (y_1,y_2,…,y_M**)**. Assuming an initial model with parameters **p** = $\mathbf{p}_0$ = (p_1,p_2,..p_N), forward computation is made to yield model vector **y** and the sensitivity or Jacobian matrix, *A*, the elements of which are partial derivatives of the model data with respect to model parameters ($A_{ij} = \partial y_i / \partial p_i$). Thus, the linearization of the problem leads to matrix equation

$$A \cdot \Delta\mathbf{p} = \mathbf{e} \, . \qquad (9)$$

Solution to Eq. (9) gives parameter update vector $\Delta\mathbf{p}$, which is then used to give updated parameter vector, $\mathbf{p}_1 = \mathbf{p}_0 + \Delta\mathbf{p}$. The process is continued iteratively until desired number of iterations has been made and/or the fit between the measured and computed data becomes small enough. The root-mean-square (RMS) error is used as the measure of the data fit

$$RMS_d = \sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(\frac{d_i - y_i}{\Delta d}\right)^2}\,, \tag{10}$$

where Δd = max(**d**)-min(**d**) is used to scale the data. The singular value decomposition (SVD) of the Jacobian is (Press et al, 1988)

$$A = U\Lambda V^T, \tag{11}$$

where U and V are matrices that contain the data eigenvectors and data eigenvectors (T means transpose operation) and Λ is a diagonal matrix that contains the singular values. Since both U and V are orthogonal matrices, the solution to Eq. (9) is

$$\Delta\mathbf{p} = V\Lambda^{-1}U^T, \tag{12}$$

where the elements of the diagonal Λ^{-1} matrix are simply $1/\lambda_i$. If some of the singular values are very small the inverse problem becomes ill-posed. Therefore, stabilization or damping is performed by adding a small value, so-called Marquart factor, β, to the singular values giving $1/(\lambda_i+\beta)$. In practice, the singular values are multiplied with damping factors (Hohmann and Raiche, 1988)

$$t_i = \begin{cases} \dfrac{s_i^4}{s_i^4 + \mu^4} & s_i \geq \mu^2 \\ 0 & s_i < \mu^2 \end{cases}\,, \tag{13}$$

where $s_i = \lambda_i / \max(\lambda)$ are normalized singular values and μ is the relative singular value threshold. Thus, elements of Λ^{-1} that correspond to very small singular values are removed totally and the remaining values are damped so that they are never too small. The damping diminishes the effect of small singular values and the threshold is used to control the strength of damping.

Thres % field defines the minimum value of the relative singular value threshold. Normally, it should be at the level of the smallest singular values that are still "informative". The threshold should be changed only if the inversion becomes unstable. Larger threshold value forces

stronger damping, which suppresses the effect of small singular values and improves the stability of the inversion. Note that the %-character is used just to remind that the value is actually multiplied by 100. Thus, the default value 0.01 is actually 10^{-4}.

F-option parameter defines the maximum parameter step for the adaptive damping (Pirttijärvi, 2003). Small value of *F-option* makes parameter steps smaller, increases the value of relative singular value threshold and thus the damping, and (usually) makes the convergence slower. Large value of *F-option* makes parameter steps bigger, reduces damping closer to that defined by minimum singular value threshold, and thus increases the convergence. However, it may also lead to unstable convergence. In practice, the *F-option* value should range between 10–0,1 and the default value 1,0 provides relatively good convergence.

The numerical computation of the SVD is the most time-consuming part of the inversion. It has approximately O^3 dependence on the total number of minor blocks. Because SVD based inversion can be time consuming, Occam methods that use iterative (conjugate gradients or QR) solvers are preferred when the number of blocks is larger than thousand or so.

5.5 Occam inversion

The famous citation from Wilhelm of Occam (Ockham) from the 14.th century states: "*Non sunt multiplicanda entia praeter necessitatem*", which translates "Plurality should not be assumed without necessity" or "One should not complicate matters beyond what is necessary". This so-called Occam's razor means that if two solutions are equally good the one that is simpler should be preferred. In geophysical inversion practice Occam's method means that in addition to minimizing the fit between the measured and computed data the roughness of the model should be minimized also. In practice, Occam inversion will produce smoother models because the neighboring density values are used as constraints. As a drawback, the models may not fit the data as well as the unconstrained (SVD) inversion. However, the so-called Lagrange multiplier (provided via *F-option* parameter) can be used to control the minimization of either the data error (fit) or model roughness (smoothness).

Occam density inversion mode optimizes the density of the free blocks. What is important in Occam inversion in practice is that if *a priori* data are available and the density of some blocks are fixed, Occam's method will constrain the parameters of the surrounding blocks to

fit those of the fixed blocks. For example, petrophysical data can be used to constrain the density at the surface.

The ability to constrain the parameter values reveals another advantage of Occam's method. The Occam inversion can create a smooth and continuous model, even if the measured data are irregularly spaced and do not cover the whole model area. In such situations the normal (unconstrained) SVD based inversion gets unstable and tends to generate very rugged (chess-board) structures.

The roughness, **r**, is defined as the difference between the density of a minor block from the mean density of the surrounding blocks, **r** = **p**-**p***. In practice, the roughness (or its reciprocal, the smoothness) is incorporated into the Eq. (9) by adding the sensitivities of the roughness ($B_{ij} = \partial r_i / \partial p_i$) and extending the data error vector with the model error **e'**, which in general is computed against some reference model, but in this case the null-model so that **e'** = **r**. Occam's method leads to a new matrix equation

$$(A + \alpha B) \cdot \Delta \mathbf{p} = (\mathbf{e}+\mathbf{e}') \,. \qquad (14)$$

where α is so-called Lagrange scaler (multiplier) that is used to emphasize either the fit between the data or the smoothness of the model.

Since the number of data M is typically equal (or smaller) than the number of blocks in the top layer, the dimension of the linear system increases quite drastically, $N \times M \rightarrow (N \times (M+N)$. In this case the SVD would become too slow to be practical. Therefore, Occam inversion uses either iterative conjugate gradient (CG) algorithm or QR decomposition (Householder rotations) to solve the matrix system for the parameter steps. The CG solver is faster than QR but it requires an additional matrix for the normal equations ($A^T A$). Therefore, CG is used as a default solver, but QR method is automatically chosen if memory cannot be allocated for the normal equations.

In *Occam density* inversion the coefficients of the linear part of base anomaly ($A+Bx+Cy$) can be optimized together with density values if the second scale widget in the right control panel is set to appropriately (*Base A, X-grad B, Y-grad C* or *Linear ABC*). The second order

coefficients cannot be optimized because they would most probably remove (or add) excess mass from the gravity anomaly itself.

F-option defines the Lagrange scaler ($L = \alpha$) in the constrained *Occam density* inversion. Lagrange scaler controls if the inversion should give more importance to minimizing the data error instead of minimizing the model roughness, or vice versa. Since both the data values and the model parameters are normalized, the default value (L= 1.0), usually gives approximately the same importance to the data and the model error. Increasing the Lagrange scaler (L> 1,0) will emphasize the importance of model roughness and the inversion will create smoother models with the expense of increased data misfit. Decreasing the Lagrange scaler (L<1,0) will emphasize the data error and the inversion will create rougher models that fit the data better.

One should experiment with different values of the Lagrange scaler and decrease it during successive iterations. When multiple iterations are made overnight, for example, automatic Lagrange scaling can be activated by giving a negative value to the *F-option* parameter (e.g., L= -1,0). The automatic value of Lagrange scaler is based on the RMS-error and the given value of *F-option*. The automatic value is always between abs(L) and abs(L)/10.

Note that the Occam inversion enforces smooth density variations. In real world the density changes are much more abrupt. The Lagrange multiplier sets a global value for the desired model roughness. The fix/free status and the discontinuity parameter provide means to define local variations in the smoothness constraint. The fix/free status imposes certain kind of rigidity around a fixed block. Additionally, discontinuity parameter can be used to define discontinuous interfaces in the model, thus, allowing rapid changes between selected two (or more) blocks.

G-scale parameter is used in Occam inversion as global data weight and it is defined separately for the gravity and each gradient components. To change the current data component one needs to use the *Gravity/Gradient* and *Grad. component* buttons. Increasing the value of global data weight increases the importance of the current data set in the inversion. On the contrary, decreasing the *G-scale* value decreases the importance of that data component. The data set can be discarded totally by setting the value of the *G-scale* parameter to zero. Note that currently the data cannot be given individual weights that would depend on the measured data error, for example. This feature may be added in the future.

5.5.1 Discontinuity

The objective of the discontinuity is to define interfaces across which the Occam method cannot continue the smoothness. In practice this is accomplished using an auxiliary discontinuity parameter stored in the model file with the help of the BLOXER program. Blocks that are marked with discontinuity information are not added to the mean of the surrounding blocks when the roughness is computed in Occam's method. The discontinuity is defined using a single (real or integer) value that consists of the sum of following values:

0	fully continuous block (normal case)
1	fully discontinuous block (special case)
2	discontinuous towards positive *x* axis (north)
4	discontinuous towards negative *x* axis (south)
8	discontinuous towards positive *y* axis (east)
16	discontinuous towards negative *y* axis (west)
32	discontinuous towards positive *z* axis (down)
64	discontinuous towards negative *z* axis (up).

For example, value 126 (2+4+8+16+32+64) means that the block is discontinuous in all directions, 30 (2+4+8+16) means that the block is horizontally discontinuous and vertically continuous, whereas value 96 (32+64) means that the block is horizontally continuous and vertically discontinuous. Discontinuity is stored into the model *.BLX files as the second parameter after the density. Likewise, value 2 means that the discontinuity interface is to the eastern side of the block. Usually, in this case the block on the eastern side will have value 4 (discontinuity is on the western side of the block). Discontinuity can be edited into the model manually or imported like topography (surfaces, lines, points) using the BLOXER program. The discontinuity information should be based on *a priori* information (or well established assumption). Please, note that this method is still under development.

5.6 Computation time

The computation time depends directly on the number of blocks and the number of points where the gravity field is to be computed. Computation of gravity gradients is slightly more time consuming and each gradient component requires some additional time. As an example, consider a model where the number of free blocks is N= 40×32×9= 11520 (the tenth layer is fixed) and the number of data points is M= 40×32= 1280. On a PC with 2.8 GHz Intel Core 2 processors the forward computation takes about 6,3 seconds using the 64-bit version of GRABLOX2 under 64-bit Window 7.

The unconstrained inversion uses computationally un-efficient SVD algorithm which has roughly O^3 dependency on the dimension of the Jacobian (sensitivity matrix). In the abovementioned example, single iteration takes over an hour (c. 70 min.) to compute and most of the time is spent on making the decomposition. Because of the slowness and the unconstrained nature the SVD inversion it should be avoided when a) the dimension of the inverse problem is large, and b) some model parameters are fixed based on a priori information.

Although Occam inversion needs to solve much larger matrix system than the SVD, the use of an iterative (conjugate gradient or QR) solver makes the overall inverse computation much faster. Considering the previous example, single iteration takes about 11-15 minutes depending on the value of Lagrange multiplier (*F-optio*n) and tolerance (*Thres %*). Most of the time is spend redefining the Jacobian, i.e., computing normal equations A^TA. The QR solver is automatically used when there is not enough memory to allocate the auxiliary A^TA matrix. In case of the 32-bit version this typically happens when N>15.000. The QR-algorithm is computationally more time consuming than CG solver (QR would take about 30 minutes for the same example) and, hence, it is used merely as an alternative solver. In the future the iterative solver is likely to be replaced with an algorithm that does not require the actual construction of the Jacobian itself.

6. Guidelines for gravity inversion

Numerical inversion of gravity data aims to obtain a model whose synthetic response fits the measured gravity data (and gradient data, if available) with sufficient accuracy. GRABLOX2 is a relatively simple software tool that can be used to determine one or few possible solutions to complicated 3-D gravity problems. The big problem, however, is the non-uniqueness of the inverse solution. One should never consider the inversion results final - they only show few possible solutions. Combined geophysical and geological interpretation is always needed to estimate the physical meaning of the inversion model and to decide whether or not the solution is acceptable.

This chapter discusses the various steps needed for the gravity inversion based on a 3-D block model and how they can be accomplished with GRABLOX2 and BLOXER. The reader should note that this chapter applies to forward modelling also. Neither the actual combined geological and geophysical interpretation nor the theory and applications of the gravity method will be discussed.

6.1 Precautions

Preliminary inspection of the data is used to assess the data quality and sampling and to give some insight to the relation between the gravity anomalies and geological structures. Computer software such as ESRI ArcGIS, Golden Software Surfer or Geosoft/ Oasis Montaj can be used to visualize the gravity, topography, and petrophysical data. Digital geological maps are also useful in the visualization of gravity and petrophysical data.

Before inversion it is also necessary to estimate the dimension of the problem. Although forward computation is quite fast, models with hundreds of thousands of blocks require lots of computer resources (CPU time and RAM). The amount of physical computer memory rarely hinders forward computation, but it may easily prevent inversion. Considering modern PC computers with multi-core processors the limit for practical inversion is about 15000 free blocks for and 1500 data points, because 32-bit Windows XP cannot allocate continuous memory for large matrices (1 GB limit). Larger inversion problems should be run on 64-bit Windows Vista or Windows 7, because they can provide the program with the full capacity of the free computer memory. Thus, the operating system and the available computer memory

and time limit the dimension and discretization of the study volume in practice. Note that the same concerns the gravity inversion of a single profile data, although much finer discretization is allowed for 2.5-D models. A rule-of-thumb states that if the forward computation takes longer than 30 seconds then the inversion must be run overnight.

6.2 Data preparation

First of all, one needs to define the gravity data for the inversion. In other words, one needs to create a column formatted data file (*.DAT) and check its format, dimensions (m, km, ml or ft), and units (mgal, Eo). The data can be evenly discretized or irregularly spaced, and it can include topography or elevation values. Remember, however, that one must choose the study area and the data sampling based on the practical limits of the inversion. For example, the inversion of 30×30 data points using a 3-D block model with 10 layers leads to a quite feasible problem of dimension $M \times N$ = 900 data points × 9000 blocks.

Pre-processing (filtering, levelling. corrections) should be made to the data beforehand. Although it is not required, the gridded data should be stored as continuous lines of *x* coordinate (from West to East) for each *y* coordinate (from South to North). If the data are measured along lines that are not aligned with main geographical coordinate axes, the coordinates should be rotated so that the new data area coincides with the coordinate axes of the model. If the data coordinates cannot be rotated the model must be made larger than data area and a certain amount of the blocks will be wasted in the corners of the model. In that case, one should hide the blocks outside the data area with the BLOXER program.

Note that data from a single profile can be interpreted using a 2.5-D model (see chapter 7.2). In that case, the data should be defined so that the profile is aligned with the x axis or y axis so that an initial 2.5D model perpendicular to the profile can be constructed (*Compute Default* menu item). Note, however, that it is possible to interpret single profile data using a fully 3D block model, although that would be somewhat ambitious.

Secondly, one needs to define the regional field if such data are available. The regional field can be included in the gravity data file or read from a separate file. In the latter case, the data should have exactly the same *x* and *y* coordinates as the gravity data. In practice, however, the

coordinates are not checked and it is therefore sufficient that the regional data have the same number of data values as the gravity data have.

Thirdly, one needs to define the gravity gradient data if such data are available. The gradient data are provided in a separate file, and need not have the same *(x,y,z)* coordinates or the data extent as the gravity data. The header of the file defines the order in which the gradient (gravity tensor) components are stored in the file. The file can contain just one or several gradient components. The diagonal elements (g_{xx}, g_{yy} and g_{zz}) of the gravity tensor are usually the most useful gradient components.

6.3 Preliminary operations

After starting up and after opening some previously defined model file (possibly a dummy file if one cancels the file open procedure), the first thing is to read in the gravity data using the *Read data* item in *File* menu. If regional gravity field is not included in the same data file it can be read in using the *Read regional data* item. Likewise, gradient data is read in using the *Read gradient data* item. The *Map data* and *Profiles* (and *Crossing dir*) buttons can be used to visualize the data as contour or image maps and profile sections. The *Gravity/Gradient* button changes the current view between gravity and gravity gradient data. The *Grad component* button changes the current view between different gradient components (if available). Note that profiles graphs are always interpolated from the (assumed) irregular data.

At this point the user should check the dimensions and use the *Gravity/Scale unit* menu item to choose between meters, kilometres or miles. This is an essential task for correct amplitude of the gravity and gradient computations. In forward modelling one should also check the *Gravity/Computation* menu item. The default option is to compute only the gravity field. Alternatively, one can compute the gravity and the vertical gradient or the gravity and the six components of the gravity tensor (g_{xx}, g_{xy}, g_{xz}, g_{yy}, g_{yz} and g_{zz}). If data have been read in the computation mode cannot be changed.

Also, one should check the method used to define the background density using *Background* item in *Gravity* menu. The default option is to use a constant value, for example, the mean petrophysical density (e.g., 2.67 g/cm^3) or zero, in which case all density values will be

relative. Alternatively one can use the mean density of the whole super block or the mean density of each layer, which should works nice with large crustal models.

Now, if the current model conforms to the problem geometry one can step into chapter 6.6. Otherwise, an initial model needs to be defined.

6.4 Initial model

When creating an initial model the user should first choose between the default (equal height) and the alternative (increasing height) block type using *Edit*/*Block type* menu item. Since the resolution of the gravity field decreases with increasing depth, the user is advised to use the alternative block type where the block height increases with depth, because the upper parts of the model can be modelled with greater accuracy with the same amount of minor blocks.

If the data are evenly discretized, the *Compute default* item in *Gravity* menu can be used to create an automatic initial model, where the minor blocks are put directly below the (regularly gridded) data points. The horizontal size, position, and discretization will be defined automatically, whereas the vertical discretization and depth to the bottom will remain the same as before, and, thus, need to be changed manually. If the data contain *z* coordinates the surface topography will be adjusted as well. If *z* coordinates are not provided the data are assumed to locate at level $z = 0$ and the top of the model is positioned accordingly. The height of the super block should be set manually so that the model does not extent too deep, but it should not be too shallow either. Usually the depth to the bottom should be 0,1–0,5 of the horizontal width of the model. In large-scale crustal studies the depth to the Moho can be imported as a boundary into the model using BLOXER. Note that especially when using gradient data better computational results are usually obtained if the depth to the top of the super block is about half of the width of the blocks. In other words, the model blocks should not be coincide with data z coordinates, otherwise the horizontal size of the individual blocks start to appear in the modelled gradient data. Depending on the data sampling and horizontal size of the blocks the effect of individual blocks can be seen in gravity data as well. Therefore, the discretization should be such that the data points are located above the centres of the blocks.

Note about editing modes: To be able to change the block size and discretization manually, one should use the *Ignore* editing mode. The *Shift* mode, which is the default mode, only allows moving the entire super block (to prevent accidental changes). Note also that the block type (equal/increasing height) cannot be changed when *Shift* mode is active. The *Preserve* mode should be reserved for changes made to an existing model, because it will use 3D interpolation to redefine existing density model inside the new model geometry.

If the data are irregularly spaced, the discretization and fine tuning of the block parameters must be checked and possibly edited manually after applying the *Compute default* button.

If topographic correction has been made to the gravity data one should use common elevation level and not the z coordinates of the data. If topographic correction has not been made one can use the z coordinates provided that the topography is relatively flat outside the study area. If the data are irregular and z coordinates are used, it is important that the top surface of the model is adjusted accordingly. First, the position, the size, and the discretization must be set manually and the model is saved into a file. Then the BLOXER program is used to import and interpolate the topography over the surface. See BLOXER's user manual to learn how to import surface topography.

Practical note: The position and the discretization of the super block should be such that the centers of the blocks locate directly below the (regularly gridded) computation points. This enables maximal relationship with the block density and the gravity field and least amount of effect due to the prism-like shape of the blocks.

If the data are highly irregular the abovementioned condition cannot be met. When dealing with regularly spaced data, however, one must remember that the corners of the super block (defined by *X* and *Y-posit* and *X* and *Y-size*) are not located below the corner points of the computation grid but the centers of the minor blocks in the corners.

Because the contour plotting used in GRABLOX2 is not very sophisticated, users are advised to use other programs (e.g., Surfer or Oasis Montaj) to interpolate the data and the *z* coordinates onto regular grids, which are then combined, edited and saved in GRABLOX2 data format (*.DAT). After this the *Compute default* option can be used to generate the initial

model. If the data coverage is not rectangular but it has irregular shape one can first create a regularly discretized initial model using the *Compute default* option. Then one can use BLOXER program to hide the blocks outside the data in which case they are considered to be equal to background density and omitted from computation and inversion.

The last step in creating the initial model is to define the initial density of the blocks. Normally, the same value is used as for the background density (e.g. 2.67 g/cm^3 or 0 g/cm^3). The density of the whole super model can be reset by defining the *Param* text field and pressing the *Reset dens* button. When performing large scale modelling the density can be set per layer using the *Edit*/*Layerwise reset* menu item. Note that resetting does not affect fixed and hidden blocks or their fix/free status.

The initial density (*Param*), background density (*Bg dens*) and the minimum and maximum value of the density range (*Min/Max density*) must also be checked before continuing with the inversion. It is also useful to save the initial model on hard disk using *File/Save model* menu item before the inversion. Note that the computational parameters (scale units, computation and background modes) and the main model parameters (position, size and discretization) are saved into the model file (*.INP), whereas the information on the individual blocks are saved into a separate block file (*.BLX). Although the whole initial model can be constructed using the BLOXER program, the computational parameters relevant to GRABLOX2 will not be included into the header of the input file (*.INP) and they need to be edited manually, preferably based on an existing model file. It is also possible to import density data from other sources or previous investigations into an existing model using the BLOXER program.

Creating the initial model is an important task that greatly affects the inversion results. Once the initial model has been defined the user can step to chapter 6.6 to interpret the data.

However, if *a priori* petrophysical or topographic data are available and used, then some additional work needs to be done.

6.5 A priori data

Two kind of *a priori* data are normally used. Either the density is known at some point on the surface based on a petrophysical data or the position of a geological contact is known based

on geological maps or previous interpretations. It is also possible that the vertical depth to a geological interface with certain density contrast can also be known based on drilling or other geophysical interpretations.

If petrophysical data are available, it should be imported into the topmost blocks of the model. First, an evenly discretized grid of the density values is made using the PETROCK program or some other suitable program (e.g., Surfer or Geosoft). The gridded data must be stored into a column formatted text file that also contains the x, y, and z coordinates of the data. Secondly, a header *.HEI file must be created where the column information of the actual petrophysical data file and its name is defined. Then the *File/Import data* menu item of the BLOXER program can be used to import the petrophysical data into the initial model. Note that the column for the *z* coordinates (*z*= 0.0) may need to be added into the file manually (use any spreadsheet program).

To enable *Import data* item in BLOXER one must first activate the *Immersion* editing mode. The *alf3/rdis* edit parameter defines the important scale distance, which normally should be equal to the horizontal size of the minor blocks. The *alf1/wght* parameter defines the weight of the existing (old) parameter value. For further information about data importing, please, consult the user manual of the BLOXER program.

Petrophysical data usually correspond only to the top layer. BLOXER's import operation, however, will extend the data to the whole model. Therefore, the density of the blocks below the first layer should be reset to background density and the top layer should be fixed (fix/free = 0) in the initial model. To accomplish this, one can use the interactive editing methods of BLOXER, but it can be done also in GRABLOX2 using *Layerwise reset* and *Layerwise fix/free* items in *Edit* menu.

In addition to surface topography, topographic information can also be used to define the vertical z coordinates of internal geological structures such as depth of the groundwater level or the depth to the basement. The depth data can be from wells, drill holes or previous geophysical or geological interpretations. BLOXER can be used to import topography data and fit the height of the blocks automatically. The topography data can be defined on a surface, along 2-D lines, or at individual points. When importing depth values along profiles or at some points, only the nearest blocks will be resized. When importing depth values as a

surface, interpolation and extrapolation are used to extend the surface horizontally across the whole model. In these operations, the top or the bottom of the closest block will be shifted to match the height value. When importing well data, the given layer is forced to fit the defined height (or depth from the surface level).

To finalize the initial model it is sometimes necessary to add margins around it. The purpose of the margins is to reduce edge effects, that is to say the gravity effect due to the density contrast between the blocks and the background density around the model. Because the block model is usually located below computation points, extending its edges outward will move the occurrence of edge-effects outside away from the computation area.

Margins can be added to the model with BLOXER or GRABLOX2 using the *Edit/Add margins* menu item. Usually multiple margins with increasing width (e.g., 100, 200, 500, 1000 m) are added to the model. Note that margins should not be used in normal 3-D density inversions, especially if regional field was defined based on large-scale inversion. Gravity gradient data, however, is more sensitive to edge-effect than the gravity data. Therefore, margins are useful when doing joint inversion of gravity and gravity gradient data.

6.6 Gravity inversion

Once the measured gravity data has been read in and a suitable initial model has been defined, the user should define the regional data if it is available and not already included into the gravity data file. Regional data is read in using *File/Read regional* menu item. The *Show/Hide regional field* item in *Edit options* sub-menu is used to include it to (or exclude from) map and profile graphs.

One should also check that the regional field is added into the computed total gravity anomaly. The total field is the sum of the computed response due to model blocks, regional field read from external file, and the base anomaly defined by the second degree polynomial function. The *Gravity field* item in *Gravity* menu can be used to define the computed field either as anomalous field or total field.

Once the data, initial model and computational parameters have been defined the user can continue the interpretation.

Usually, the first step is to compute the response of the initial model pressing *Compute* button. Then one can use the *Map data* and *Profiles* buttons to inspect the measured and computed data and their difference. The base anomaly and the user defined regional field can be shown and hidden using the *Show/Hide regional* item in *Edit* menu. At this point one needs to check that the dimensions (m vs. km) are defined correctly. Comparing the contour/image map of the data and the layer map of the model one can also see if the model corresponds to the current data. The grid lines of the minor blocks (*Edit options/Grid lines*) and the dots of the data (if labels are shown) shown in contour/image maps of the data can also be used to check proper model discretization.

Often there is a strong difference in the base level of the computed and measured gravity field. This is natural since the measured data are relative and the 3-D model does not compute with absolute gravity values. Thus, the base response should be optimized first.

6.6.1 Base anomaly inversion

Optimization of the coefficients of the base anomaly is a simple, but essential part of the interpretation process, particularly if no other means are used to define the base level or regional trend. The base anomaly is defined as a polynomial of the second degree. Base anomaly optimization is selected from the uppermost list widget on the right control panel. The second list widget is then used to define the combination of the coefficients of the base anomaly that will be optimized:

1. *None* none of the base response components is not optimized (default),
2. *Base* only the base level (*A*) is optimized,
3. *X grad* only the x gradient (*B*) is optimized,
4. *Y grad* only the y gradient (*C*) is optimized,
5. *X2* only the *D* coefficient is optimized,
6. *Y2* only the *E* coefficient is optimized,
7. *XY* only the *F* coefficient is optimized,
8. *Linear* the linear coefficients are optimized (*A, B, C*),
9. *All* all coefficients are optimized (*A, B, C, D, E, F*).

If the difference between the measured and computed data is considerable, one should first optimize only the base level. After selecting the base response optimization and its combination one needs to press the *Optimize* button to do the inverse iterations, the number of

which are defined by the *Iters* text field. Before inversion one forward computation of the whole model is also performed.

Usually, the change in the fit between measured and computed data due to the base response optimization is best seen in profile response graphs. Once the base level is fitted reasonably well one can include the *x* and *y* gradients into the optimization. Note that in 2.5-D inversion if the data are defined along x and y directed profiles only the x or y dependent coefficients (*A, B,* and *D* or *A, C* and *E*) can be optimized.

The optimization of the base anomaly tries to fit both positive and negative gravity anomalies to minimize the data misfit. Negative gravity anomalies, however, require negative density contrast corresponding to mass deficiency ("negative mass"). Therefore, after optimization of the base anomaly, especially when using absolute (*a priori*) density values, it is necessary to adjust (usually decrease) the base level of the base anomaly so that mainly positive gravity anomalies remain.

Note about base level inversion: The base anomaly can be biased towards the bottom level of the gravity anomaly by increasing the *I-option* parameter in the left control panel. The bigger its value (IOPT= 1–10) the further downwards the base level will be positioned in base level inversion. Negative value of *I-option* parameter will shift the base anomaly towards the top level of the gravity anomaly, which is useful when interpreting sediment formations with negative density contrast. Note that the biasing method of the base anomaly does not work when base level is optimized together with density values in Occam inversion.

Finally, note that the menu item *Comp -> Regi* can be used to cast the current computed data onto the regional data. If the model is a so-called zero-model, that is, the block densities are equal to the background density or the super block is temporarily located very deep, the computed data will be equal to the base response ($g_c = g_b$). By using the *Remove regional* menu item one can subtract the base anomaly from the measured data. In most cases this will clarify the inspection of the contour and image maps of the gravity data and will bring up more details. See chapter 5.1 for more information about regional field.

Once the base level has been defined the actual 3-D density inversion can start.

6.6.2 Density inversion

Once the gravity data and the initial model have been defined and the base anomaly and the possible regional data have been set by optimization or by other means, one can proceed with the density inversion. The objective of the 3-D gravity inversion is to find out the absolute or relative density variations below the study area where the gravity field has been measured. Considering a 3-D block model this means the optimization of the density of the minor blocks so that the data error, i.e., the difference between the measured and the computed data, is minimized.

Two different density inversion methods are currently used in GRABLOX2. The unconstrained *Density* inversion uses the old SVD based algorithm and should be used only when using rather small models. Because *Density* inversion is an unconstrained it should be used only if there are no fixed blocks (*a priori* information) even if additional constraining is used. The *Occam d* inversion is a constrained inversion method that minimizes the model error (roughness of the model) together with the data error. The *Occam d* inversion is preferred because it can better utilize *a priori* (petrophysical) density information.

To perform the actual density inversion one needs to run several iterations. If the inversion takes lots of time, multiple iterations should be run overnight. In *Occam d* inversion the initial value of the Lagrange multiplier should be set equal to the default value (L= 1,0) so that the densities get better adjusted with fixed blocks. The L-value can be decreased at later iterations to produce better data fit. Very small L-value (L< 0.1) should be avoided, because it can disturb the smoothness of the density of upper parts of the model. Automatic L-value can be set by giving it a negative value.

When using petrophysical *a priori* data to fix the density of the surface layer (or some parts of it) one can optimize the base level of the base anomaly together with density. Because depth weighting always puts certain amount of mass to the bottom of the model the density values of the free blocks may not get adjusted properly with the fixed density values of the surface if base level is fixed. In principle, it would be advantageous if the initial density of the free blocks is equal to the background density which is equal to the minimum density, because the inversion would then need to generate only positive gravity effects and positive density contrasts. The use "negative" mass that appears when minimum density is smaller than the

background density allows faster convergence. By changing the regional level the user can try to affect to the abundance of positive and negative masses.

The models resulting from block model inversion, particularly from the Occam inversion, are rather smooth and special care must be taken when assessing the actual properties and density values of the geological models that they are interpreted to represent. Also, the user must always remember that gravity inversion has no unique solution – an infinite number of possible models can fit the measured data equally well. To test the validity of the model, the density values and fix/free status can be edited manually using the BLOXER program and the differences in the fit of the various models can be used to assess the limiting values of density, depth and depth extent that are usually the most interesting quantities of the interpretation.

Due to the nature of gravity data one should bear in mind that the horizontal variation of the density distribution is easier to interpret, but the depth to the top and the depth extent of the targets are very difficult to interpret using a block model. For this purpose, the results of 3-D block model interpretation can be used as an initial model for the interpretation programs that use parametric models (e.g., Modelvision). The migration from the 3-D block model to parametric models might be implemented in future GRABLOX2 or BLOXER versions.

6.7 Post-processing

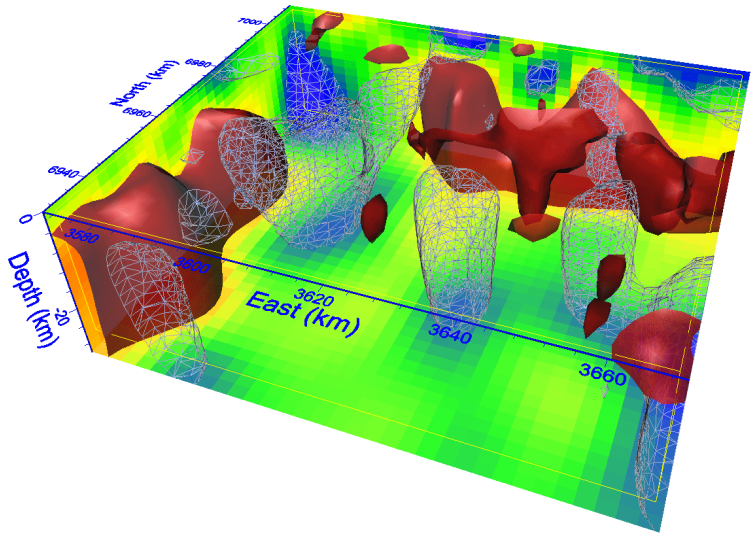
As discussed in the beginning of this chapter, the user must finally decide whether the resulting inversion model is physically and geologically acceptable or not. Due to the non-uniqueness of the gravity problem, the resulting inversion model is only one of the many possible solutions. At the moment GRABLOX2 does not provide any detailed information about the resolution of the inverse solution. The user can try to assess the validity of the solution by making changes into the model and investigating how the changes affect the computed gravity. Moreover, by using a completely different initial model one can try to estimate the robustness of the solution. Often this part of the interpretation process is the most time consuming.

After the actual interpretation has been made the user would probably like to present the results graphically. Unfortunately, the plotting capabilities and the quality of GRABLOX2 and BLOXER printing are quite poor. Users are advised to use external plotting programs

such as Surfer or Geosoft/Oasis-Montaj to prepare maps for published reports. The synthetic data computed for the interpretation model and the measured data are saved in column formatted text files using the *File-Save data* menu item. The inversion results (information text) and the synthetic data will be saved in text files using *File-Save results* menu item.

Note about forward computation: When a model based on a previous inversion is opened the forward computations are made on a regular grid using a constant *z* coordinate value (height), which is equal to the top of the super block or the value given by *Z-level* parameter. So, if the original data (on which the model was based) were irregularly spaced or the data had *z* coordinates the computed gravity anomaly will be different from the previous inversion results. Therefore, to re-compute the synthetic data at correct data position and elevation, the measured gravity data (and regional field and gradient data) must be read in.

Although the block data are stored in column formatted text files (*.BLX), they have a format of their own, where the *z* coordinates are attached to the top of the minor blocks. Moreover, if the alternative block type is used, the z coordinates are not equally spaced. Thus, to plot the model data with external software one should use BLOXER's *File/Export data* menu item to interpolate the block data on an evenly sampled grid. The export operation shifts the z coordinates from the top of the block to the middle of the block and adds additional layers when the alternative block type used. A special output format allows saving the data in a format suitable for Fortner's Transform T3D program that can be used to create more advanced 3-D views of the density data with transparency and perspective views. Voxler by Golden Software is another recommended 3D visualization software.



Example of Voxler's visualization of a 3D density model: solid red iso-surfaces delineate high density areas whereas low density areas are shown by mesh lines only.

7. File formats

7.1 Model files

The following example illustrates the format of the input model *.INP file:

```
     3    2.03
 -250.00   -250.00   250.00   250.00   50.00   25.00   25.00   25.00   0.00  0.00
   0    0    0    0    1    0    0    0
 .10000E+01    10.00    0.00    0.00    0.00    0.00    0.00    0.00   0.00
-275.000    -262.500   0.000    550.000    525.000    300.000
  11   21    8
   1    2    0
   1
   1848    1    1
   0 0.100000E+01 0.500000E+00 0.200000E+01 0.100000E+01
```

- Line 1 defines the *number of lines* (NOL=3) that are specific to the GRABLOX2 and the *version number* of the model file (VER=2.0). Depending on the version number GRABLOX2 reads the following NOL lines a bit differently. Note, that GRABLOX2 dependent lines will be skipped over by BLOXER.
- Line 2 defines the *computation grid*: *X-start & Y-start* (-250, -250), *X-end & Y-end* (+250, +250), *X-step & Y-step* for gravity (50, 25) and gradient data (25, 25) and *Z-level* for gravity and gradient data (0, 0). Note that the data elevation is defined as a positive value if the level is above the surface ($z = 0$).
- Line 3 defines the *background density* (*d0*, g/cm^3), and the coefficients of the base anomaly (*A, B, C, D, E, F*) and its shifted origin (*x0, y0*). Note that *B* and *C* have been multiplied by 1000 (mgal/km) and *D, E* and *F* are multiplied by 10^6 (mgal/km^2).
- Line 4 defines some computational options: a) *Dimension*: 1= meters, 2= kilometers, 3= miles, 4= feet, b) *Computation mode*: 0= block gravity, 1= point gravity, 2= vertical gradient, c) *Gravity fiel*d: 0= anomalous field, 1= total field, d) *Background density*: 0= given value, 1= mean layer density, 2= mean-block density, e) *Parameter roughness*: 0= not defined, 1= defined. The remaining three parameters are reserved for future use.
- Line 5 defines the *x*, *y* and *z* coordinates of the top-south-western corner of the super block (*X0, Y0, Z0*), and the size of the super block in *x*, *y* and *z* directions (*dX, dY, dZ*). Note that the depth is defined as a positive value if it below the surface ($z = 0$).

- Line 6 defines discretizations (number of blocks) in *x*, *y* and *z* directions (*Nx, Ny, Nz*).
- Line 7 defines some properties of the block file: *The first parameter* defines the block (*.BLX) file format (IFO): 0 = The *.BLX file does not exist (the block model will be generated automatically), 1= Normal text file and real (floating point) values, 2= Normal text file and 2-byte integer values, 3= Binary file and real (floating point) values, 4= Binary file and 2-byte integer values, 5= Binary file and 2-byte integer values, the byte order of which are reversed when the data file is being read (allows Unix ↔ PC conversion). *The second parameter* defines the *block type*. If IBO= 1 all blocks are assumed to have equal height (default), and if IBO= 2 the block height is increasing with depth. If IBO < 0 then block reduction has been used (see BLOXER documentation). The 3.rd parameter is reserved for future use.
- The parameter on the 8.th line defines the zooming level (IZO= 1, 2, 3, …, 10).
- If the zooming level were bigger than 1, the next line would contain the *x*, *y*, and *z* coordinates of the center of the zoom-block, and the dimension of the zoom-block in *x*, *y* and *z* directions. GRABLOX2 does not utilize the zoom options at all.
- The ninth line (in this case) defines the number of blocks (NOB), the number of parameters (NOP), and the index number of the column (ICO) that contains the density values to be read in from the *.BLX file. Note that if block reduction had been used and the block file would have been saved using the *File-Save red. model* menu item, the number of actual minor blocks might be smaller than the value based on discretization.
- The last line contains parameters defining density: 1) *Scale type*: 0= linear scale, 1= logarithmic scale, 2) *Default value* (used instead of that at the 3.rd line), 3) *Minimum value* (for color scale and inversion limits), 4) *Maximum value* (for color scale and inversion limits), and 5) *Scaling factor* (multiplier for labels in layer and section views).

When gravity gradients are computed the model file is slightly different. If the model is made for vertical gradient computations there will be an additional line that defines the global weight (*G-scale*) and the base anomaly parameters of the vertical gradient data. If the model is made for full gravity tensor computations there will six additional lines after the line that defines the base anomaly line of the gravity data. The order or rows correspond to g_{xx}, g_{xy}, g_{xz}, g_{yy}, g_{yz} and g_{zz} components. As with vertical gradient case, the first parameter is the global weight (*G-scale*) of each gradient data component.

Considering vertical gradient data the model file will look something like this:

```
   4    2.01
  -250.000   -250.000    250.000    250.000     50.000     25.000   0.000   0.00
   0    1    0    0    1    0    0    0
   1.0000   10.000    0.000    0.000    0.000    0.000    0.000    0.00    0.00
   1.000    0.000    0.000    0.000    0.000    0.000    0.000    0.00    0.00
   -275.000    -262.500       0.000     550.000     525.000     300.000
...
```

In principle there is no need to edit model files manually. However, if the *.BLX file is missing one can still open the model by resetting the file format parameter (IFO= 0) on the 7.th line so that a dummy block model will be generated automatically. Also, if the *.BLX file was generated using reverse binary INT*2 format of Unix/Sun/Mac, the model can be opened by resetting the file format parameter (IFO=5). Note that binary files with real (floating point) values cannot be transported across different computer platforms.

The *.BLX file has simple column format, where the columns correspond to: the *x, y, z* size of the blocks (columns 1–3), the *x, y, z* position of the blocks (columns 4–6), the fix/free/hidden/ reduced block status (column) 7, and the parameter columns (8–17). Normally, the density values are in the 8.th column. If discontinuity information is utilized it must be defined as the second parameter so it is stored next to density values (9.th column). The horizontal (*x*, *y*) position of a minor block is fixed to the center of the rectangular block area, but its vertical *z* position is fixed to the top of the block. Moreover, for the block model the positive *z* axis points downwards so normally the z coordinates of the blocks are positive. This may be somewhat misleading since the data z coordinates (topography and elevation) increase upwards. Note that the order of the do-loops used to save the model data is: *z* loop, *y* loop, *x* loop. This means that for each layer (from top to bottom) the blocks are saved so that for each *y* coordinate value (from South to North) the data is saved along x-axis (from West to East). Please, see the user's manual of the BLOXER program for additional information considering the block model.

Note that when *Autosave* option is enabled, the model files (*.INP & *.BLX) are saved during each iteration so that the user can study them afterwards. The files are named GRABLOX2_AUTOFILE_XXX.*, where XXX tells the number of iteration. These files are

saved in the current working directory. Even if *Autosave* is not enabled, the model of the latest iteration is saved in the program folder. These model files are named as GRABLOX2_CURRENT_ITER.*.

7.2 Gravity data files

The default extension of gravity data files is *.DAT. Interactive input of gravity data from generic column formatted text files is possible if the first character on the first line is a one of the comment characters; "!", "#" or "/". In this case the user is asked to provide all the necessary column information interactively. Otherwise, the file is assumed to contain a header that defines how to read the file directly without user intervention.

The example below illustrates the format of a *.DAT file used for (measured) gravity data:

```
Example gravity data

153 1 2 0 3 0

 -200.00  -200.00  0.2007733E-01
 -150.00  -200.00  0.2855821E-01
 -100.00  -200.00  0.3860382E-01
  -50.00  -200.00  0.4719916E-01
    0.00  -200.00  0.5056060E-01
etc ...
```

The first line is a header that will be used in the response graphs as a secondary title. The header line can be empty. Lines starting with "!", "/", or "#" characters will be considered as comment lines. The 3.rd line contains six integer values:

1. The total number of data points, *M*
2. The column index of the *x* (east) coordinate, *ix*
3. The column index of the *y* (north) coordinate, *iy*
4. The column index of the *z* (topography) coordinate, *iz*
5. The column index of the gravity data, *id*
6. The column index of the regional data, *ir*.

The order of data columns can be arbitrary. The columns of x and y coordinates, however, must be defined before actual data columns. If the column index of the z coordinate is zero then the data are assumed constant value defined by the *Z-level* parameter in the left control panel.

Profile data can be defined using three alternative methods. If the column index of the x or the y coordinate is zero (*ix* = 0 or *iy* = 0), the corresponding coordinate is considered to be missing and the data will be put along the *x* axis (*iy* = 0) or the y axis (*ix* = 0). For interpretation purposes one should reformat data files to pass the profile distance coordinate as x or y coordinates so that an default initial model can be computed automatically. For modelling purposes a generic measurement profile from (*x*1, *y*1) to (*xM*, *yM*) is assumed if the column indices of the x and y coordinates have opposite signs. Thus, if the example would read "`153 1 -2 0 3 0`", the data would be handled as general single profile data (*Y-step* = 0).

The abovementioned file format is used also when data are saved into a file using the *Save data* item in *File* menu. Note that the resulting order of the columns depends on the existence of measured data and regional field, which are also added to the saved data file.

7.3 Gradient data files

The default extension of gravity gradient data files is *.GAT. Interactive input of gravity gradient data from generic column formatted text files is possible if the first character on the first line is a one of the comment characters; "!", "#" or "/". In this case the user is asked to provide all the necessary column information interactively. Otherwise, the file is assumed to contain a header that defines how to read the file directly.

```
Example gradient data

# X, Y, Z, Grav, Gxx, Gyy, Gzz

  231   1   2   3   7   3
  5  0  0  6  0  7

 -250 -250  20  0.100494E+02  0.733776E+00  0.273901E+01 -0.347278E+01
 -200 -250  20  0.100644E+02 -0.137107E+01  0.552706E+01 -0.415600E+01
 -150 -250  20  0.100799E+02 -0.431615E+01  0.908393E+01 -0.476777E+01
 -100 -250  20  0.100921E+02 -0.692114E+01  0.121797E+02 -0.525863E+01
  -50 -250  20  0.100974E+02 -0.795603E+01  0.135430E+02 -0.558699E+01
    0 -250  20  0.100951E+02 -0.734493E+01  0.130158E+02 -0.567088E+01
  etc ...
```

The first line is a header that will be used in the gradient response graphs as a secondary title. The header line can be empty. Lines starting with "!", "/", or "#" characters will be considered comment lines. The fifth line (in this case) contains six integer values that are:

1. The total number of data points, *M*
2. The column index of the *x* (east) coordinate, *ix*
3. The column index of the *y* (north) coordinate, *iy*
4. The column index of the *z* (topography or elevation) coordinate, *iz*
5. The total number of data columns (including coordinates), *it*
6. The number of data columns to be read in, *id*

The next line defines the column indices of the gradient data corresponding to the six tensor components: 1= g_{xx}, 2= g_{xy}, 3= g_{xz}, 4= g_{yy}, 5= g_{yz}, 6= g_{zz}. Column index equal to zero means that the corresponding component will not be read. Thus, the example above defines g_{xx}, g_{yy} and g_{zz} components in columns 5, 6 and 7. Note that the order in which the components need to be defined is fixed, but the columns themselves can be in arbitrary order.

A special case is reserved for the vertical gradient data. In this case the second parameter line (`"5  0  0  6  0  7"`) is not needed and the fifth line could read `" 231  1  2  3  7  1"`. Thus, if the total number of gradient data columns is set equal to one (*id*=1), the file is assumed to contain only vertical gradient which will be read from the column indicated by the

total number of columns (*it*). Note, however, that the format shown in the example can be used to define vertical gradient data as well (data columns are "0 0 0 0 0 7").

Profile data can be defined using two alternative methods. Firstly, if the column index of the x or the y coordinate is set zero (*ix* = 0 or *iy* = 0), the corresponding coordinate is considered to be missing and the data will be put along the *x* axis (*iy* = 0) or the y axis (*ix* = 0). Secondly, data are assumed to correspond to a straight measurement profile from (*x*1, *y*1) to (*xM*, *yM*) if the column indices of the x and y data have opposite signs. Thus, if the example would read "231 1 -2 3 7 3", the data would be handled as general single profile data (*Y-step* = 0).

GRABLOX2 cannot be used to interpret gradient data without any gravity data. Although gravity and gradient data can be defined independently (different x and y coordinates, sampling and elevation) they both need to be defined consistently. This means that both gravity and gradient data need to be defined either along two profiles or two 2D map areas. Note, however, that the data extent (*X-start, Y-start, X-end, Y-end*) and the computation of the default initial model are based on gravity data.

7.4 Output files

Information about the model and system parameters used in the computation are stored in the results file (*.OUT). The result file also contains information about the inversion. Since the file format is self-explaining it will not be described here.

7.5 Graph options

Several graph related parameters are defined in the GRABLOX2.DIS file. One can edit the *.DIS file manually, restart the program or use the *File/Read disp* menu item make the changes visible. If the format of the file should get corrupted, one should delete the *.DIS file and a new one with default values will be generated automatically the next time the program is started. Except for the top part of the file shown below, the format of GRABLOX2.DIS file is self-explaining since it defines the various text strings used in the graphs.

```
Grablox 2.0 graph parameters

  36   32   24   24   22
   1    1    1    0    0    1    1
 300  460    0    1    1    0    0
0.60 0.85 0.00 0.00 0.00 0.00
 200.  30.   4.

Gravity field modeling and inversion
Gravity anomaly
Gravity gradient
Computed
Measured
Regional
Difference
X / East
Y / North
Z / Depth
Distance
Density (g/cm^3$)
Log10(Density)
(mGal)
(Eötvös)
```

- The first line is a title that defines the version number.
- The second line defines the five character heights used for: 1) the main title and the graph axis titles, 2) the axis labels, 3) the plot legend text, 4) the model description text, and 5) the axis labels in the 3-D model view.
- The next line has some integer values that modify the graph appearance:
  1. include/exclude (1/0) the model information text in the graphs,
  2. include/exclude (1/0) the small 3D model view in the graphs,
  3. set the corner where the legend text will be positioned. Values 1-4 put the legend in SW, SE, NE or NW corner of the page (outside the graph). Values 5-8 put the legend in the SW, SE, NE, or NW corner inside the graph.
  4. set the color scale: 0= rainbow, 1= reverse rainbow, 2= grayscale, 3= reverse grayscale, and 4= temperature (red) scale,
  5. set normal/widescreen (0/1) display mode,
  6. show/hide (1/0) labels in layer maps,

7. show/hide (1/0) grid lines in data maps and layer maps.

- The next line has more integer values that modify the graph appearance:
  1. *x* (horizontal) offset (in pixels) of the origin from the left side of the page,
  2. *y* (vertical) offset (in pixels) of the origin the bottom of the page,
  3. create either contour or image maps (0/1),
  4. show/hide (1/0) regional field when data maps are shown,
  5. show/hide (1/0) data error (difference) when data maps are shown,
  6. show the difference as absolute values or as percents (0/1).
- The next line with numerical values defines: 1) the length of the longest axis relative to the size of the remaining (origin shifted) width and height of the plot area. The 4.th line defines horizontal and vertical viewing angles and a (relative) viewing distance used in the 3-D model views.
- The last line with numerical floating point values defines the horizontal and vertical angle and the relative distance of the view point for the 3D model view.
- The remaining lines define various character strings for the graphs. The maximum length of the strings is 70 characters. Note the special use of caret "^" symbol for displaying the superscript (exponent) in the density unit (g/cm^3). The dollar sign "$" sets the text level back to normal. Subscripts can be generated with the help of "]" control character. See DISLIN manuals for further information.

8. Additional information

I made the first GRABLOX version in 2003 when I worked at the Geological Survey of Finland in the 3-D crustal model (3DCM) project funded by the Academy of Finland. Because of the many requests I made GRABLOX version 1.5 freely available in 2005. Several fixes and updates to the computation, inversion and graphical user interface were implemented in version 1.6 released in 2008. GRABLOX2, which was released in December 2009, was rewritten to comply with gravity gradient data. So as not to make things too complicated it does not contain block height inversion anymore.

The forward computation is based on the GPRISM algorithm by Sven-Erik Hjelt (1974). The equations for gravity gradients are provided Zhang et al. (2000) but the algorithm is adapted from Hjelt's (1972) solution for the magnetic field of a magnetized prism. The idea of depth weighting has been discussed by Li and Oldenburg (1996 & 1998). The linearized inversion has been described by Jupp & Vozoff (1975) and Hohmann & Raiche (1988). The adaptive damping has been described in my PhD thesis (Pirttijärvi, 2003). The constrained Occam inversion is based on the paper by Constable et al. (1987). The SVD and the conjugate gradient solver algorithms have been adapted from Press et al. (1988). The QR decomposition algorithm, originally by Lawson & Hanson (1974), was found from Alan Miller's webpage (http://users.bigpond.net.au/amiller/).

The program is written mostly in standard Fortran 90 but it contains some extensions of Intel Fortran version 11.1. The user interface and the graphics are based on DISLIN graphics library (version 9.5) by Helmut Michels (http://www.dislin.de). Because DISLIN is independent form the operating system the program can be compiled and run on other operating systems (Linux or Mac OS X) without major modifications. This requires that DISLIN and some necessary libraries and a Fortran 90 compiler have been properly installed. However, the source code of GRABLOX2 is not publicly available at the moment. If you have suggestions for improvements, please, inform me.

Because GRABLOX2 is still under development this user guide may not describe all the latest changes and additions made to the software. Additional information may be obtained from author's WWW-site at: http://www.cc.oulu.fi/~mpi/.

8.1 Terms of use and disclaimer

You can use the GRABLOX2 program free of charge. If you find the program useful, please, send me a postcard.

The GRABLOX2 software is provided as is. The Author, University of Oulu and Geological Survey of Finland disclaim all warranties, either expressed or implied, with regard to this software. In no event shall the Author, University of Oulu and Geological Survey of Finland be liable for any indirect or consequential damages or any damages whatsoever resulting from loss of use, data or profits, arising out of or in connection with the use or performance of this software.

8.2 Contact information

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9. References

Blakely, R.J., 1995. Potential Theory in Gravity and Magnetic Applications. Cambridge University Press. 441 pp.

Constable, S.C., Parker, R.L. & Constable, C.G., 1987. Occam's inversion - A practical algorithm for generating smooth models from electromagnetic sounding data, Geophysics, 52, 289–300.

Hohmann G.W. and Raiche A.P., 1988. Inversion of controlled-source electromagnetic data. In: Nabighian, M.N. (Ed.) Electromagnetic methods in applied geophysics, Volume 1, Theory. Soc. of Expl. Geophys., Tulsa, p. 469-503.

Hjelt S.-E., 1972: Magnetostatic anomalies of dipping prisms. Geoexploration, 10, 239-254.

Hjelt S.-E., 1974. The gravity anomaly of a dipping prism. Geoexploration, 12, 29-39.

Jupp D.L.B and Vozoff K.,1975. Stable iterative methods for the inversion of geophysical data. Geophys. J. R. Astr. Soc. 42: 957-976.

Lawson, C.L. & Hanson, R.J., 1974. Solving least squares problems. Prentice-Hall.

Li, Y. and Oldenburg, D.W., 1996. 3-D inversion of magnetic data. Geophysics, 61, 394-408.

Li Y. and Oldenburg D.W., 1998. 3-D inversion of gravity data. Geophysics, 63, 109-119.

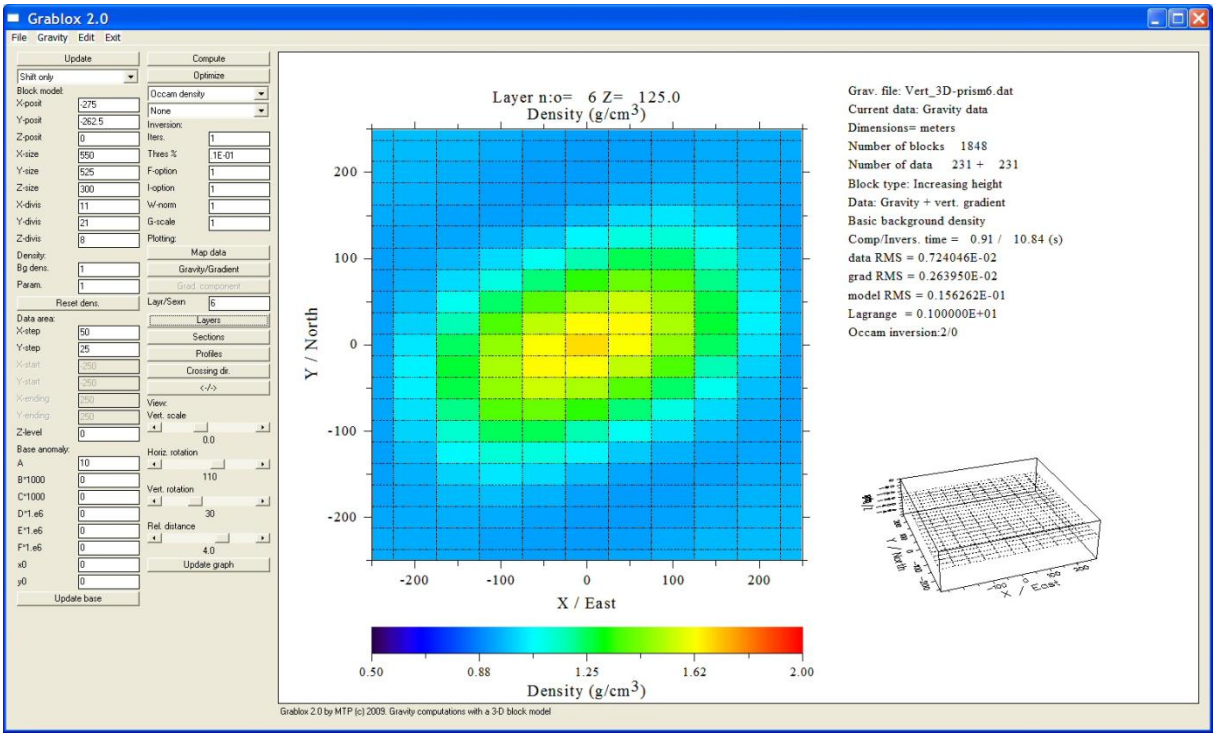
Pirttijärvi M., 2003. Numerical modeling and inversion of geophysical electromagnetic measurements using a thin plate model. PhD thesis, Acta Univ. Oul. A403, Univ. of Oulu.

Pirttijärvi M., 2005. BLOXER - Interactive visualization and editing software for 3-D block models, Version 1.5a, User's guide, University of Oulu, 38 pp. <http://www.cc.oulu.fi/~mpi/Softat/pdfs/Bloxer_manu.pdf>

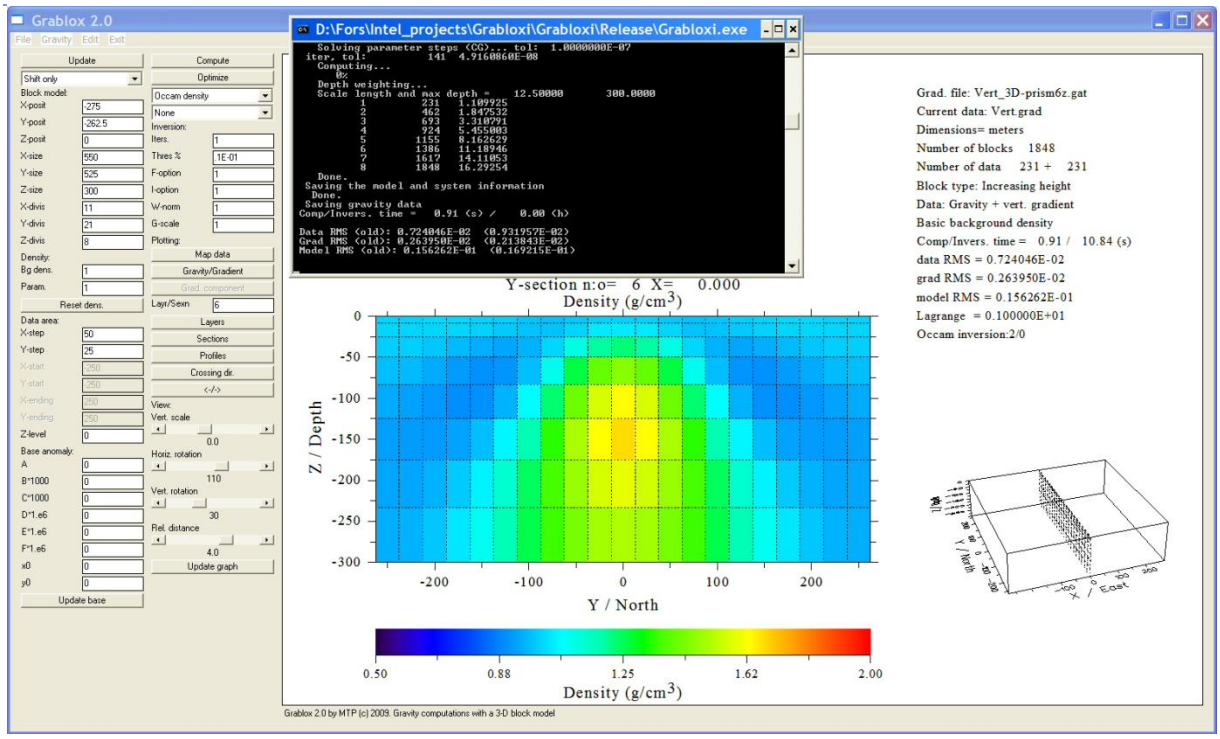
Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T., 1988. Numerical recipes, the art of scientific computing. Cambridge University Press.

Zhang C., Mushayandebvu M.F., Reid A.B., Fairhead J.D. and Odegard M.E., 2000. Euler deconvolution of gravity tensor gradient data. Geophysics, 65, 512–520.

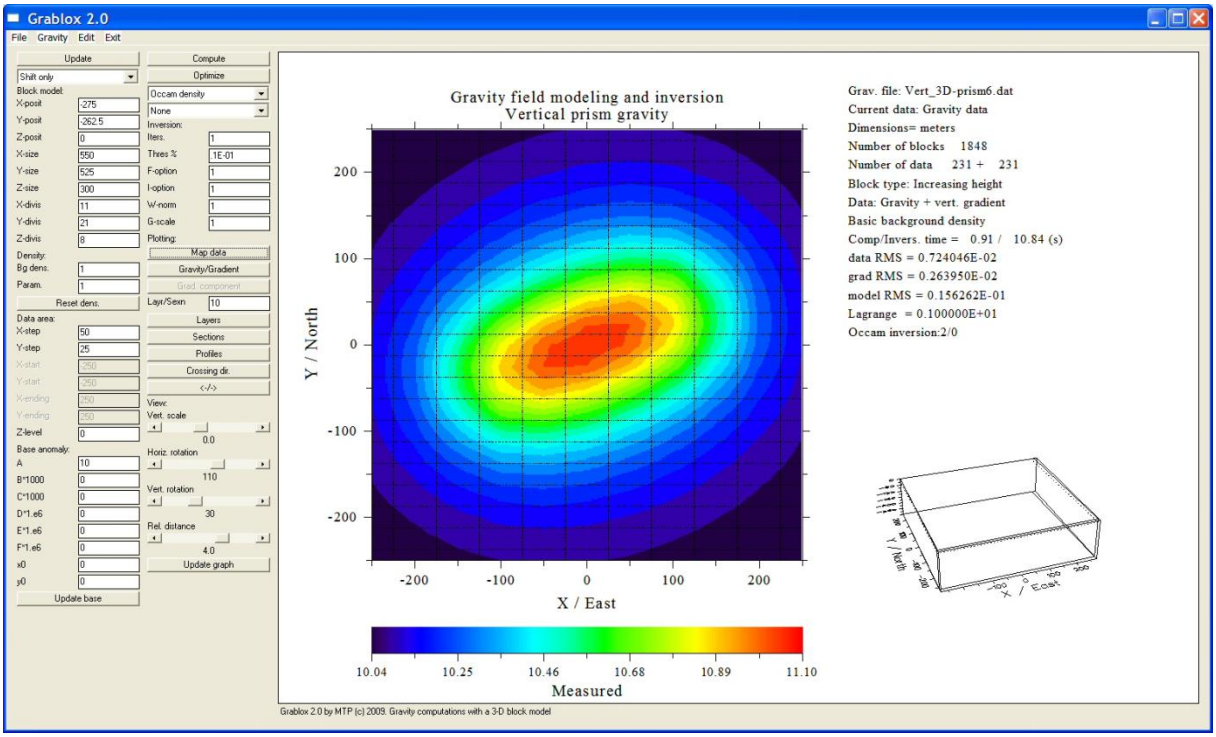
Appendix A1: Layer map of the 3D block model



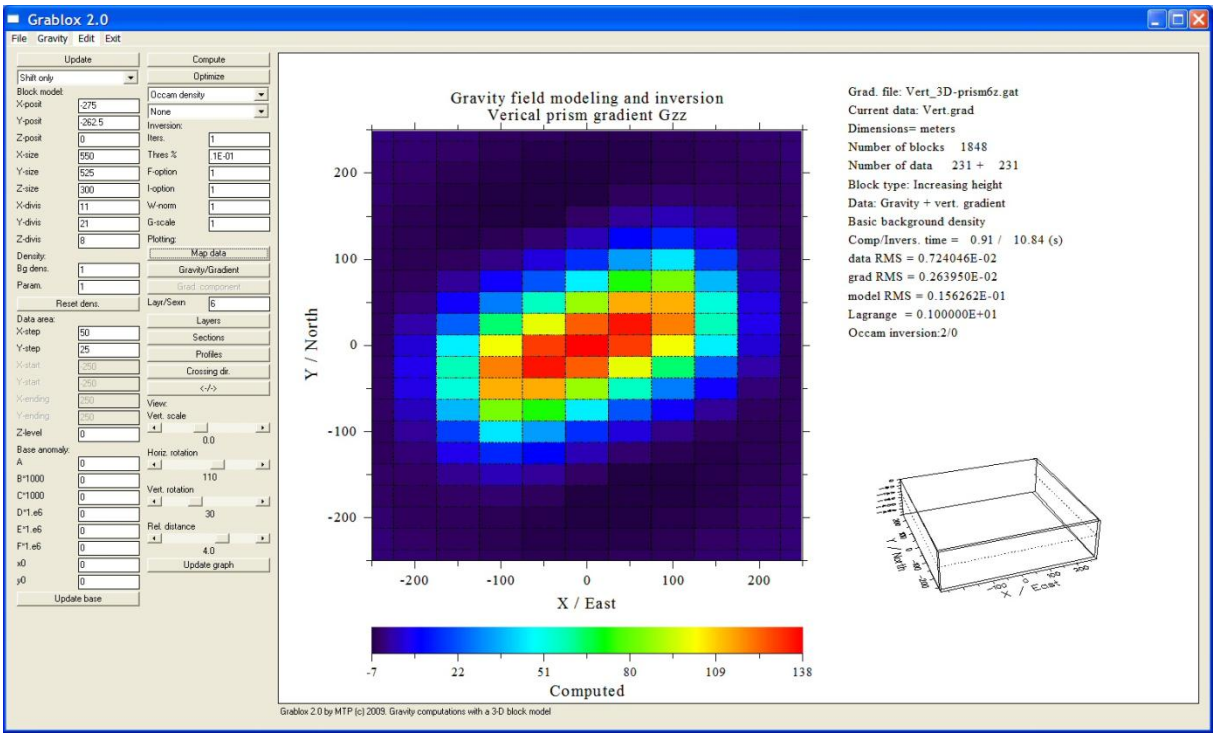
Appendix A2: Section map of the 3D block model & the console window



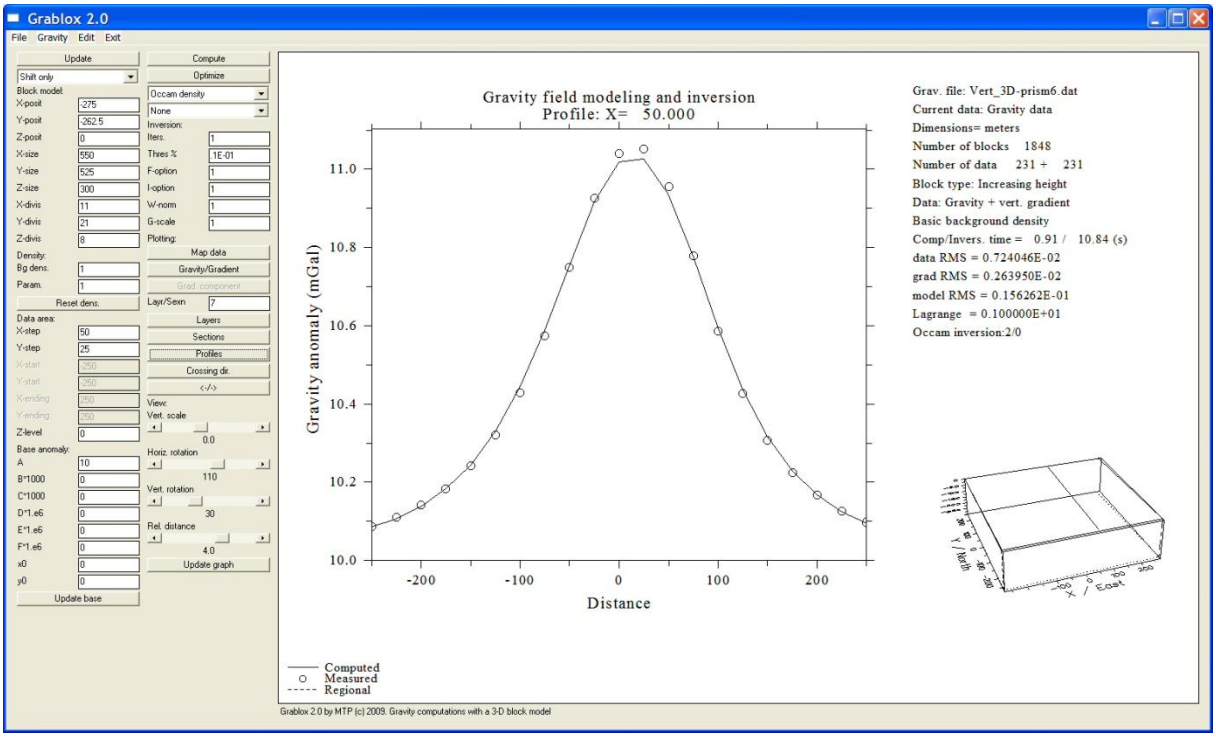
Appendix B1: Contour map of the measured gravity data


Grablox 2.0
File Gravity Edit Exit
Gravity field modeling and inversion
Vertical prism gravity
Y / North
X / East
Measured
10.04 10.25 10.46 10.68 10.89 11.10
Grav. file: Vert_3D-prism6.dat
Current data: Gravity data
Dimensions= meters
Number of blocks 1848
Number of data 231 + 231
Block type: Increasing height
Data: Gravity + vert. gradient
Basic background density
Comp/Invers. time = 0.91 / 10.84 (s)
data RMS = 0.724046E-02
grad RMS = 0.263950E-02
model RMS = 0.156262E-01
Lagrange = 0.100000E+01
Occam inversion:2/0
Grablox 2.0 by MTP (c) 2009. Gravity computations with a 3-D block model

Appendix B2: Image map of the computed vertical gradient data


Grablox 2.0
File Gravity Edit Exit
Gravity field modeling and inversion
Verical prism gradient Gzz
Y / North
X / East
Computed
-7 22 51 80 109 138
Grad. file: Vert_3D-prism6z.gat
Current data: Vert.grad
Dimensions= meters
Number of blocks 1848
Number of data 231 + 231
Block type: Increasing height
Data: Gravity + vert. gradient
Basic background density
Comp/Invers. time = 0.91 / 10.84 (s)
data RMS = 0.724046E-02
grad RMS = 0.263950E-02
model RMS = 0.156262E-01
Lagrange = 0.100000E+01
Occam inversion:2/0
Grablox 2.0 by MTP (c) 2009. Gravity computations with a 3-D block model

Appendix C1: Profile plot of the gravity data



Appendix C2: Profile plot of the gravity gradient data